



## **Technologies for production of Electricity and Heat in Sweden. Wind energy in perspective of international development**

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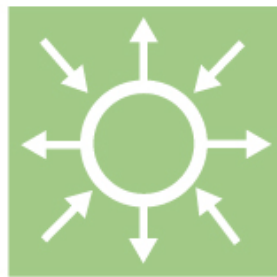
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# Technologies for production of Electricity and Heat in Sweden

Wind Energy – in perspective of international development

Elforsk rapport 2500



Niels-Erik Clausen, Henrik Lawaetz, Jørgen Lemming, and Poul Erik Morthorst  
December 2008

# Technologies for production of Electricity and Heat in Sweden Wind Energy in perspective of international development

Niels-Erik Clausen, Henrik Lawaetz, Jørgen Lemming and  
Poul Erik Morthorst

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**Abstract (max. 2000 char.):**

The development of the wind energy technology has been very successful from the 1970's and up till now. Initially there was a battle between wind turbine concepts, but the commercial winner today is the three-bladed horizontal axis, upwind, electricity producing and grid connected wind turbine with availability on mature markets somewhere around 99%.

An important contributor to the growth of the European market for wind energy technology has been EU framework legislation combined with legislation at the national level. The binding target for renewable energy in Sweden is proposed to be 49% of the final energy consumption in 2020 compared to 39.8% in 2005.

To stimulate the development of wind energy and to promote a specific national goals Sweden is mainly using an electricity certificate system. The target is to increase the production of electricity from renewable sources by 17 TWh in 2016, relative to corresponding production in 2002. There is not at specific target for the use of wind energy.

A future energy system that includes a high proportion of wind energy will be expected to meet the same requirements for security of supply and economic efficiency as the energy systems of today. The variability of wind power create a specific challenges for the future energy systems compared to those of today.

The economics of wind power depends mainly of investment cost, operation and maintenance costs, electricity production and turbine lifetime. An average turbine installed in Europe has a total investment cost of 1.230 €/kW with a typically variation from approximately 1000 €/kW to approximately 1400 €/kW.

The calculated costs per kWh wind generated power range from approximately 7-10 c€/kWh at sites with low average wind speeds to approximately 5-6.5 c€/kWh at good coastal positions, with an average of approximately 7c€/kWh at a medium wind site. Offshore costs are largely dependent on weather and wave conditions, water depth, and distance to the coast. The cost of wind generated power is higher for offshore wind farms that for on land ones ranging from approximately 6 c€/kWh to more than 9 c€/kWh.

Assuming a learning rate at 10% and a doubling time of total installed capacity of four years the cost interval would in 2015 be approximately 4.8 to 5.5 c€/kWh for a coastal and inland site, respectively.

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# Preface

The present report is one out of six in a series of reports in the project “Inventering av framtidens produktionstekniker för el och värme” (technologies for production of electricity and heat). The project is financially supported by Elforsk, Stockholm.

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Niels-Erik Clausen



## **Executive summary**

### **Technology**

The development of the wind energy technology has been very successful from the 1970's and up till now. Initially there was a battle between wind turbine concepts from the 1970's till the early nineties. A great variety of concepts were tested during this period – e.g. horizontal axis wind turbines with one, two, three and four blades, downwind and upwind turbines, pitch, stall or yaw controlled turbines, and vertical axis wind turbines, e.g. Darrieus, the gyro-turbine and others. The commercial winner today is the three-bladed horizontal axis, upwind, electricity producing and grid connected wind turbine.

In the 1970's the reliability and availability of the first generations of wind turbines were quite low. In the 1980's and 90's the reliability and availability in general reached an acceptable level of more than 95%, and today the availability on mature markets lies somewhere around 99%. This has been achieved supported by a regime of extensive certification and testing schemes, which has required wind turbine manufacturers to prove their engineering integrity, safety and quality issues as well as performance of the wind turbines.

Although in general the future technological development of wind energy is expected to be mainly incremental fundamental research is still important to maintain the innovation in the industry. While the first offshore wind turbines were basically identical to land based turbines, it is expected that in the future offshore wind turbines will be increasingly designed for offshore applications or even for specific projects. As the onshore development is more mature than offshore wind technology new innovative concepts are more likely to appear for offshore applications.

### **Small off-grid wind energy**

In general it is considered that small wind turbines have a large potential in off-grid applications, particularly in isolated small grids in rural regions of developing countries. So far the market for small wind turbines is still not considered mature and prices per kWh electricity are still significantly higher than that produced by grid connected wind turbines.

In remote applications a high technical availability of the technology is crucial to provide the needed security of supply. On the other hand the alternatives are often no power or power at a cost significantly higher than the cost of electricity in large grids. A recent study (ref 21) has evaluated reliability of the small wind turbines and results show a promising low frequency of failures for the small wind turbines at a level comparable to or even lower than for large wind turbines. On the other hand the downtime associated with each failure was found to be significantly larger than that of large wind turbines (from 2 to 25 days depending of the nature of the failure compared to 1-2 days). The reason for this could be that small wind turbines are often manufactured and sold by relatively small companies with relatively few employees and very often limited or no resources allocated to service.

## **Policy and planning**

### **Target for renewables**

All countries recognize the need to reduce carbon emissions and maintain that renewable energy in general offer great potential to reduce overall carbon emission of the power industry. In addition, reducing the cost and security issues of using imported fuels is an element of several national targets. Establishing various types of national objectives or targets is used to define goals, develop policies, measure progress, and revise policies and goals as needed along the way.

An important contributor to the growth of the European market for wind energy technology has been EU framework legislation combined with legislation at the national level, aimed at reducing barriers to the development of wind energy and other renewables. The new binding EU target is that 20% of Europe's energy should be provided by renewables in 2020. There is a specific sectoral target for biofuels of 10% by 2020, but no target for renewable electricity or individual technologies such as wind power.

The binding target for renewable energy in Sweden is proposed to be 49% of the final energy consumption in 2020 compared to 39.8% in 2005.

### **Incentives**

The most commonly used incentives in countries are related to investment, production and market.

Incentive programs that help offset the capital cost of wind farm development to varying degrees have been successful in several countries. Programs range from direct investment subsidies of 30- 50 %, over subsidies of different part of projects to subsidies of installation costs for demonstration projects.

Price incentives (feed-in tariffs) are paid to operators according to the amount of electrical generation of the wind project, thus rewarding productivity. Tariffs can also be used to promote specific national goals and have stimulated wind farm development in several countries. This type of support system is widely used in Europe and has jumpstarted the development of wind energy in Denmark, Germany and Spain.

A certificate system is a support system based on market conditions. Producers receive a certificate and consumers or suppliers are obliged to buy a certain quantity. Incentives for producers therefore correspond to price they can get for the certificates on the market.

Other kinds of support have accelerated the development of wind energy in countries. For example comprehensive Wind Energy Atlas that allows planners of wind energy projects to generate a detailed picture of wind patterns for any location. And in Germany and Denmark, Federal authorities have identified suitable areas for offshore wind farms in the North Sea and Baltic Sea, making planning easier for investors.

Changing the rules governing subsidies can have dramatic effects on the wind energy market. Especially stop-and-go effects have had a negative effect in several countries (e.g. USA).

### **The electricity certificate system**

In May 2003 Sweden introduced an electricity certificate system. The target is now to increase the production of electricity from renewable sources by 17 TWh in 2016, relative to corresponding production in 2002. The quantity of certificates to be purchased increases from year to year in step with progressive increases of the quota proportion, thus generating a corresponding increase in demand for the certificates.

The electricity certificate system is intended to support the construction of new plants for the production of electricity from renewable energy sources and from peat. However, in order to limit the cost to consumers of electricity from such sources as older, commercially viable plants, there is a time limit on the right of producers to receive certificates.

Plants commissioned after the start of the electricity certificate system are entitled to receive electricity certificates for 15 years and plants that were started up before are typical entitled to certificates until the end of 2012. This will have the effect of reducing electricity production from renewable energy sources and from peat in the system, thus also reducing the number of certificates available.

For production, there is no goal for wind energy alone. The production goal in the electricity certificate system applies to new renewable energy in general. The electricity mix in Sweden is dominated by nuclear power and hydropower. Hydropower production varies from year to year according to the amount of yearly rainfall.

For offshore wind power, the subsidy system is not sufficient for deployments to take off. There are no goals for offshore wind as such, but the Swedish Government has had a special funding program for market introduction for large-scale plants offshore and in arctic areas with the intention to speed up the expansion of wind power in these large areas of Sweden.

For projects below 25 MW all permitting matters are handled by the local municipality. Projects bigger than 25 MW are handled by the county administration (onshore permitting) or by the Environmental Courts for offshore permitting.

### **System aspects**

A future energy system that includes a high proportion of renewable energy will be expected to meet the same requirements for security of supply and economic efficiency as the energy systems of today, while delivering better environmental performance, especially with regard to CO<sub>2</sub> emissions. Security of supply refers to the long-term reliability of fuel supply; especially in power systems, it also covers short-term requirements for system stability and adequacy. Economic efficiency is concerned with getting the best from the significant amounts of money, human capital and natural resources involved in an energy system. Integral to economic efficiency in energy systems is the presence of well-functioning markets for energy services. The variability and reduced predictability of a number of renewable energy sources, notably wind power, create specific challenges for future energy systems compared to those of today. Power transmission will also become an issue, as the areas with good potential for wind power are often located some distance from the centers of power consumption.

Large wind farms such as the 160 MW Horns Rev and the 165 MW Nysted offshore wind farms in Denmark are connected to the transmission system, in a sense that

make them comparable to conventional power plant blocks. To obtain the maximum benefit from an overall power system, wind power should be able to replace the operation of conventional thermal power plants, so that the fuel consumption and emissions can be reduced. To do this effectively, wind power plants need to possess some of the major characteristics of conventional power plants. One of these characteristics is the ability to control the amount and quality of the power produced. Modern wind turbine technologies make it possible to control both active and reactive power. The possible power production from a wind power plant is obviously limited by the available power in the wind. Since the fuel is free the impact on operational cost for a wind farm is very limited when power output is reduced below the available power in the wind. Still, such reduced production can be beneficial in the overall system for periods where the market price of electricity is low or zero. In Denmark, this sometimes happens in cold and windy periods. Previously the electricity supply to the system was increased in cold periods because the Combined Heat- and Power Plants (CHP) plants have to run at high heat production and were obliged also to produce electricity for the grid. Recently, CHP plants are producing power also on market conditions and therefore the flexibility in the system is higher as the CHP plants are allowed to run in heat mode only.

The technical challenges to system operation and the power market are mainly about building a stable and reliable power system that contains a large scale of renewable energy to replace conventional power plants. In this context, a more specific challenge is to reduce the need to run conventional power plants at low output during periods when generation from wind power or other renewables is high. In such periods, conventional plants are kept running to provide ancillary services such as voltage and frequency support. The cost of the resulting power is high, in environmental as well as economic terms, because plants running below full capacity tend to be less efficient and more polluting. From an overall system point of view, therefore, it could sometimes be useful to use renewable generators to provide these ancillary services, even though this would reduce the total production from renewables.

## **R&D**

Sweden is today characterized by not having any major wind turbine industry. Therefore most of the projects<sup>1</sup> over the last years have been related to the siting of wind farm and the integration of wind power into the grid system. Elforsk, the Swedish Electricity Utilities' R&D company, manages the program. Basic research projects are funded 100% by the Swedish Energy Agency and applied projects are typically funded 60% by Elforsk and 40% by the Swedish Energy Agency. The program is user-oriented and has strong co-operation between the utilities and the grid owners (including the Swedish TSO). Areas of research interests include grid integration, external conditions, standards, O&M, project development, impacts on the environment, and public acceptance.

Apart from projects in these programs R&D projects regarding mapping the wind climate in Sweden and conflicts with the military radar reconnaissance also have been funded. To improve market competition and to help the development of new turbines that can lower the cost of electricity, the Swedish Energy Agency has funding a special demonstration project of a 3.5-MW turbine with a new direct-driven generator, NewGen. The recipient of the financial support for the demonstration project is Vattenfall AB. The turbine is expected to be in operation by

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<sup>1</sup> 2006 IEA Wind Energy Annual Report and the Elforsk Program: Vindforsk 2003-2006 and 2006-2008

mid-2009. The generator will cut weight by approximately 70% compared with a conventional direct-driven generator, which is believed to cut generator cost by about half and make the drive train investment cost comparable to that for a conventional gearbox/high-speed generator concept. The benefit of the direct driven generator will be a reduced number of components, better reliability, and reduced O&M costs.

Continued R&D is considered to be essential to provide the necessary reductions in cost and for future installation not least for offshore applications. It can therefore be recommended, that Sweden continue to fund R&D projects within the different wind energy areas.

Future R&D must also include incremental improvements in, for example, understanding extreme wind situations and reducing system weight and cost.

Future research projects should therefore be supported within areas such as:

- a) Reduction of uncertainties
- b) Cost reduction
- c) Enable large-scale use
- d) Minimise environmental impacts
- e) Wind within future energy supply systems.
- f) Wind energy in combination with long and short term energy storage hydrogen and other renewables.

An important element in connection with turbine R&D is access to good test facilities. Generally there is a need for more test facilities for both onshore and offshore wind turbines to be able to test large blades, drive trains and new materials to verify models and to test turbines in harsh environment like offshore and cold climate.

## **Cost of land based wind power**

Relatively few parameters are governing the economics of wind power:

- 1. Investment costs, incl. auxiliary costs for foundation, grid-connection etc.
- 2. Operation and maintenance costs
- 3. Electricity production / average wind speed
- 4. Turbine lifetime
- 5. Discount rate.

Of these, the most important parameters are the turbines' electricity production and their investment costs. As electricity production is highly dependent on wind conditions, choosing the right turbine site is critical to achieving economic viability.

Capital costs of wind energy projects are dominated by the cost of the wind turbine itself. Thus, an average turbine installed in Europe has a total investment cost of approx. 1.23 Mill. €/MW, that is a 2 MW machine costs around 2.5 Mill. € including all additional costs for foundation, electrical installation, consultancy etc. The turbine's share of total cost is on average approximately 76%, while other important cost components are grid-connection and foundation accounting for approximately 9% and 7%, respectively. The total cost per kW installed wind power capacity differs significantly between countries. The cost per kW typically varies from approximately 1000 €/kW to approximately 1400 €/kW. Investment costs per kW

were found to be lowest in Denmark and approximately 5-10% higher in Greece and Netherlands. For Sweden, UK, Spain and Germany the costs were found to be approximately 20 to 40% higher compared to Denmark.

Operation and maintenance (O&M) costs constitute a sizeable share of the total annual costs of a wind turbine. For a new turbine O&M costs might easily have an average share over the lifetime of the turbine of approximately 20-25 percent of total levelled cost per kWh produced – as long the turbine is fairly new the share might constitute 10-15 percent increasing to at least 20-35 percent by the end of the turbine's lifetime. Thus O&M costs are increasingly attracting more attention manufacturers attempting to lower these significantly by developing new turbine designs requiring fewer regular service visits while maintaining a high availability of the turbines.

The calculated costs per kWh wind generated power range from approximately 7-10 c€/kWh at sites with low average wind speeds to approximately 5-6.5 c€/kWh at good coastal positions, with an average of approximately 7 c€/kWh at a medium wind site. In Europe coastal positions as these are mostly to be found at the coast of UK, Ireland, France, Denmark and Norway. Medium wind areas are mostly to be found as inland terrain in Mid- and Southern-Europe, that is Germany, France, Spain, Holland, Italy, but also as inland sites in Northern Europe in Sweden, Finland and Denmark. In many cases local conditions do significantly influence the average wind speed at the specific site for which reason strong fluctuations in the wind regime are to be expected even for neighboring areas. Owing to trends towards larger turbines, lower investment costs and more efficient designs implying higher production the cost of wind generated power has decreased for a number of years. However, this trend was broken in 2006 where total investment costs rose by approximately 20% compared to 2004, mainly induced by a strong increase in demand for wind turbines combined with severe supply constraints.

Based on the experience curve approach the cost of wind generated power was estimated until 2015 for Danish conditions assuming a learning rate at 10%. At present the production costs for a 2 MW wind turbine installed in a Danish area with a medium wind speed (inland position) is approximately 6.1 c€/kWh wind produced power. If sited at a coastal position costs today are approx. 5.3 c€/kWh. If a doubling time of total installed capacity of three years was assumed the cost interval would in 2015 be approximately 4.3 to 5.0 c€/kWh for a coastal and inland site, respectively. A doubling time of five years, would imply a cost interval in 2015 of 4.8 to 5.5 c€/kWh. As mentioned Denmark is a fairly cheap wind power country. For more expensive countries the cost of wind power produced will increase by 1- 2 c€/kWh.

### **Costs of offshore wind power**

Offshore wind only counts for a small amount of total installed wind power capacity – approx. 1% - and development has mainly taken place in North European countries mainly round the North Sea and the Baltic Sea, where by now a little more than 20 projects have been implemented. At the end of 2006 almost 900 MW of capacity was located offshore in five countries: Sweden, Denmark, Ireland, Netherlands and the United Kingdom.

Offshore costs are largely dependent on weather and wave conditions, water depth, and distance to the coast. Based on detailed cost information on recent offshore installations it is found that investment costs per MW range from a low of 1.2 mill. €/MW at the Danish Middelgrunden to more than the double of 2.7 mill. €/MW at the British Robin Rigg. The recently developed Swedish offshore wind farm

Lillgrunden cost approximately 1.8 mill. €MW. However, the abovementioned costs only to a limited extent reflect the recent price increases in the wind power industry. Thus, on average investment costs for a new offshore wind farm today are expected to be in the range of 2.0 to 2.2 mill. €MW for a near-shore shallow depth (< 20 m) facility.

The higher capital costs of offshore are due to the larger structures and complex logistics of installing the towers. The costs of offshore foundations, construction, installations, and grid connection are significantly higher than for onshore. For example, typically, offshore turbines are 20% more expensive, and towers and foundations cost more than 2.5 times the price for a project of similar size onshore.

The cost of wind generated power is higher for offshore wind farms than for on land ones ranging from approximately 6 c€/kWh to more than 9 c€/kWh. Though the costs are considerably higher for offshore wind farms this is to a certain degree moderated by a higher total electricity production from the turbines due to higher offshore wind speeds. For an on-land installation the number of full-load hours is normally around 2000-2300 hours per year, while a typical offshore installation enjoys 3000 hours per year or above. Observe that these costs are calculated as simple national economic ones and will not be those of a private investor, which will have higher financial costs, including a risk premium and a profit.

Based on the experience curve approach the future cost development of offshore turbines is analyzed until year 2015. On average cost of offshore wind capacity is calculated to decrease from 2.1 mill. €MW in 2006 to 1.81 mill. €MW in 2015 or by approx. 15%. A considerable spread of costs will exist, from 1.55 mill. €MW to 2.06 mill. €MW. A capacity factor of constant 37.5% (corresponding to a number of full load hours of approx. 3300) is expected in the period, covering an increasing production from newer and larger turbines moderated by sites with lower wind regimes and increasing distance to shore and thus increasing losses in transmission of power.

## **Scenario for deployment of wind power**

A rapid development in the global utilization of wind power has taken place over the last 10 years. At the end 2007, about 1% of the global electricity consumption was produced by wind power.

Based on existing studies on future wind power development Risø DTU has evaluated future opportunities in wind power and calculated a future scenario for wind power deployment.

In this scenario total wind power production (on land and offshore) is calculated to be 10,100 TWh in 2050, wind power supplying approx. 25% of global electricity consumption. The assumed growth implies that the accumulated global wind power capacity will double each 3<sup>rd</sup> year until 2015, each 4<sup>th</sup> year from 2015-20, and, each 7<sup>th</sup> year from 2020-30. In the period 2030-50 growth is assumed to be much slower. In the long term average cost of on land wind capacity is calculated to decrease from 1.2 mill. €MW in 2006 to 0.83 mill. €MW in 2050 or by approx. 30%. It should be strictly underlined that these results are subject to large uncertainties.

At present several offshore wind farms are under construction in UK waters (Robin Rigg, Rhyl Flats, Inner Dowsing and Lynn) and in Dutch waters the second offshore farm Q7-WP consisting of 60 2 MW turbines will be operational in 2008. And much more offshore capacity is in the planning stages. In the United Kingdom, for

example, London Array Limited received consent in December 2006 for the world's largest offshore wind farm to be built in the London Array. At 1,000 MW of capacity, it will be capable of powering one-quarter of the homes in London. In Denmark another 2 times 200 MW will be installed in 2009 and 2010.

In the future scenario total offshore wind power production is calculated to 2,559 TWh in 2050, offshore wind power supplying a little more than 6% of global final electricity consumption and constituting approx. 18.4% of total wind power capacity. The assumed growth implies that the accumulated global offshore wind power capacity will double each 2<sup>nd</sup> to 3<sup>rd</sup> year until 2015, each 3<sup>th</sup> year from 2015-20, and, finally, each 5<sup>th</sup> year from 2020-30. In the long term average cost of offshore wind capacity is calculated to decrease from 2.1 mill.€/MW in 2006 to 1.35 mill€/MW in 2050 or by approx. 35%.

## **Future studies**

Many challenges prevail for development of wind energy on a large scale in Europe. At the last European Wind Energy Conference in Brussels (EWEC 2008) two key challenges were identified: Access to the grid and integration of large amount of wind energy and lack of qualified professionals to ensure a continued growth of the industry.

Within the IEA Wind Implementing Agreement the following topics has been identified as the most important concerning grid-integration of wind energy.

1. Large scale grid integration; modelling and management of load flows within national and international high voltage transmission networks.
2. Distributed generation; modelling the system response to wind energy embedded in the low voltage distribution networks.
3. The development of detailed models, describing turbine and large wind farm electrical behaviour.
4. Better forecasting techniques increasing the value of wind energy by allowing electricity production to be forecasted from 6 to 48 hours in advance.
5. Improved electrical storage techniques for different time scales (minutes to months) will increase value at penetration levels above 15 to 20%.
6. Regeneration and active demand side management.
7. Energy storage.
8. The value and benefits of combining wind energy with other technologies such as hydro and PV.
9. The organisational and legal framework for transmission and distribution system operators to provide a safe and reliable electricity supply.

In addition to that we may add (with a view to the Nordic countries):

10. Wind energy application in forests
11. Strategies for operation and maintenance – especially for large offshore wind farms
12. Increase the number of young people entering university educations like e.g. engineers and other specialists needed in the wind energy industry as a whole
13. Public acceptance of land based wind energy



# 1 Wind energy technology

## 1.1 Grid connected turbines

The development of the wind energy technology has been very successful from the 1970's and up till now. We have seen a battle between the different wind turbine concepts from the 1970's till the beginning of the nineties. A great variety of concepts were involved during this period – e.g. horizontal axis wind turbines with one, two, three and four blades, downwind and upwind turbines, pitch, stall or yaw controlled turbines, and vertical axis wind turbines, e.g. Darrieus, the gyro-turbine and others. Based on earlier experiences from the 50'ies prototypes of MW turbines were developed in national programs USA, Germany, Sweden and Denmark, but it was the industrial development of small scale turbines at 15-55 kW that became the start of what we to day know as the wind turbine industry. The commercial winner today is the three-bladed horizontal axis, upwind, electricity producing and grid connected wind turbine. Figure.1 show how the size of the turbines has increased since 1980. The largest wind turbines on the global market today are around 5 MW with a rotor diameter of up to 120 meters. Up to 2005 the size of turbines have doubled every 5 years, but a slow down is expected over next the 5 year period.

In the 1970's the reliability and availability of the first generations of wind turbines were quite low. In the 1980's and 90's the reliability and availability in general reached an acceptable level of more than 95% [ref.7], and today the availability on mature markets lies somewhere around 99%. This position has been achieved by means of a regime of very extensive certification and testing schemes, which has required the wind turbine manufacturers to prove their engineering integrity and the safety, quality and performance of the wind turbines. Such certification schemes are required by governments in some countries and in others by the market agents.

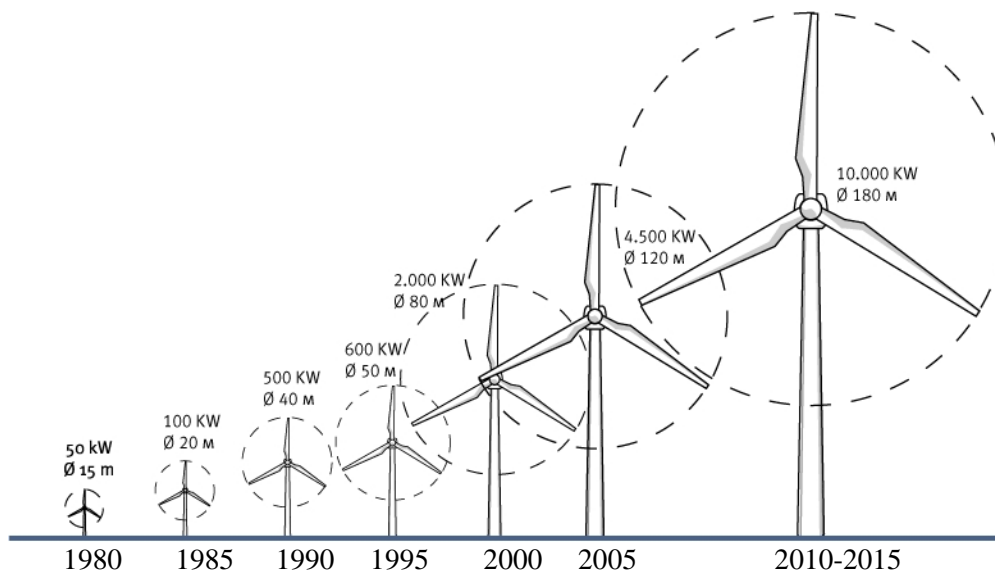


Figure.1: Development in wind turbine sizes from 1980 to 2005.

The technical challenge of developing large turbines of increasing size and complexity with a new technology based on state-of-the art research in a number of fields such as aerodynamics, aero elasticity, new materials and condition monitoring, requires new and more advanced methods for design and testing in order to ensure satisfactory reliability. Also the larger turbine components are more difficult to transport from one place to another, especially on land.

Most of the world electrical generation capacity from wind power plants is still land based, except a small number of offshore installations, which have been built over the last 10 years especially in the Northern Europe. In terms of installed capacity [MW] offshore wind farms accounts for approximately 1% of the accumulated capacity in the World as well as of the installed capacity in 2007.

In 2005, the best-selling turbines on the World market had a rated capacity of more than 1.5 MW, and these machines had a market share of more than 40%. But turbines with capacities of 1 to 1.5 MW are still important having a market share of almost 35%. Finally, the smaller turbines with capacities of 750 to 1000 kW had a market share of 20%. Large wind turbines with a capacity of 2.5 MW and above are getting increasingly important and accounts for 6% of the installed capacity in the year 2007 (2.3% in 2005) .

#### **1.1.1 Improvement in efficiency**

The wind regime at the chosen site, the hub height of the turbines and the efficiency of production mainly determine power production from the turbines. Thus, increasing the height of the turbines has by itself yielded a higher power production. Similarly, the methods for measuring and evaluating the wind speed at a given site have improved substantially in recent years and thus improved the siting of new turbines. In spite of this, the fast development of wind power capacity in a few countries such as Germany and Denmark implies that most of the good wind sites by now are taken and, therefore, new on-land turbine capacity has to be erected at sites with a marginally lower average wind speed.

The development of electricity production efficiency owing to better equipment design measured as annual energy production per unit swept rotor area (kWh/m<sup>2</sup>) at a specific reference site has correspondingly improved significantly over the last years. Taking into account all the three mentioned issues of improved equipment efficiency, improved turbine siting and higher hub height the overall efficiency has increased by 2 to 3 percent annually over the last 15 years.

#### **1.1.2 Future technological development**

In the long-term perspective the offshore technology development has to be seen in relation to areas as aerodynamics, structural dynamics, structural design, machine elements, electrical design and grid integration. The development can be structured in:

- Incremental developments
- New main component concepts
- New wind turbine concepts

Right from the start back in the 1970s the wind turbine industry has been characterized by *incremental development*. In the future this development is especially to be seen in the following areas:

- Development of more efficient methods to determine wind resources

- Development of more efficient methods to determine the external design conditions e.g. normal and extreme wind conditions, wave conditions, ice conditions etc.
- Development of more efficient methods to design and construct the wind turbines blades, transmission and conversion system, load carrying structure, control system and grid interconnection system. Condition monitoring can through the introduction of new and more advanced sensor systems open up for the development of important improvements of the reliability of offshore wind turbines which can be crucial for the development of more cost efficient and competitive technology
- Innovations with more efficient designs, introduction of new control elements e.g. new sensor systems, more intelligent communication between wind turbines, and introduction of new more advanced materials.
- Innovations in the wind turbine production, transportation and installation methods.

The incremental development of the technology is where the main research and development priority is in the industry and in the research community. The learning (cost reduction) in the industry comes from a combination of incremental development in design and construction of wind turbines and cost reduction due to increased production volume.

Development of *new main components concepts* has also been seen from the mid 1970s and new component concepts competes with existing concepts and thereby is continuously a challenge for the existing main component concepts. The main areas for the competition today are:

- New wind turbine blade concepts with new materials, new structural designs and new aerodynamic features
- New transmission and conversion systems e.g. wind turbines with gearboxes versus wind turbines without gearboxes with multi-pole generators
- New electrical generator concepts
- New power electronic concepts
- New grid integration concepts
- New foundation concepts e.g. gravitation foundations, monopole foundations, tripod foundations and floating wind turbines

The development of new main component concepts is a very dynamic part of the technology development of the wind energy field and opens often up for new innovative components. This development is extremely dependent of a very reliable verification of the performance of the new component concepts through research and experimental verification.

In general the future technological development of offshore wind energy is expected to be mainly incremental and more fundamental research is very important to continue the innovation in the industry. In the future development it might prove to be important to distinguish offshore wind turbines from onshore ones. The onshore development is more mature than offshore wind technology and new innovative concepts are more likely for offshore applications.

The development offshore goes from shallow water to very deep water. The development until now is mainly seen in areas with shallow water. Technologies used offshore are expected to differ depending on the water depth and can be divided into:

- Shallow water
- Intermediate depth (50 m > depth > 20 m) bottom mounted
- Floating concepts

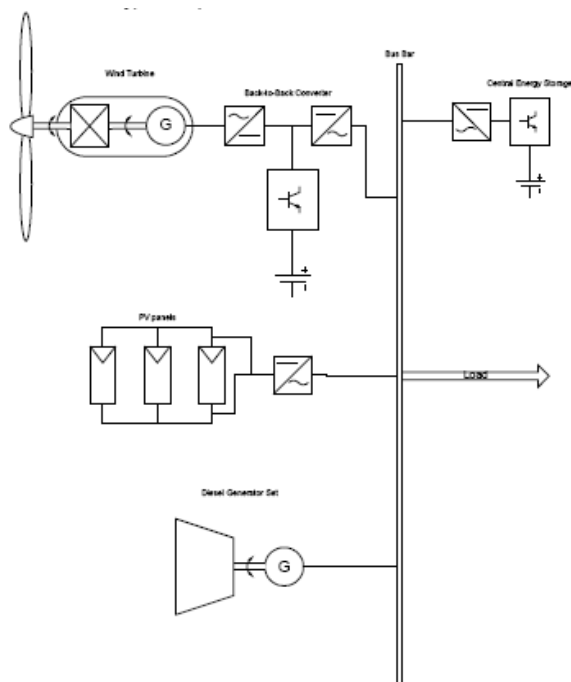
It should be mentioned that availability and reliability is crucial for the development of a competitive offshore wind energy technology and will in coming years be the dominating factor for the development.

In general the future technological development of offshore wind energy is expected to be mainly incremental and more fundamental research is very important to continue the innovation in the industry. While the first offshore wind turbines were basically identical to land based turbines, it is expected that in the future offshore wind turbines will be increasingly designed for offshore applications or even for specific projects. As the onshore development is more mature than offshore wind technology new innovative concepts are more likely to appear for offshore applications.

## 1.2 Stand alone (non-grid connected) wind turbines

Stand alone wind turbines are turbines in an isolated power system without connection to a public grid. The systems typical ranges from very small (micro) turbines less than 1 kW used in individual households up to isolated grids to about 100 MW where wind power is combined with oil or natural gas fired power plants.

The basic concept is to have stand alone turbine to perform equivalently to a diesel generator set in terms of controllability of voltage and power. It should therefore be able to act as a unit in a power system with other types of generation. These other types of generation normally include conventional diesel generator and energy storage but PV panels or small hydro can also be connected as shown in Figure 2.



*Figure 2: Typical system configuration. The units except stand-alone wind turbine and load are optional. There can be more than one of all the units. (ref Stand-alone version of the 11kW Gaia wind turbine Risø-R-1480(EN) September 2004)*

### **1.2.1 General requirements**

Wind turbines are normally designed to be connected to a grid where other equipment controls frequency and voltage. Often, they also require a source of reactive power in order to produce power. This is e.g. the case for wind turbines using induction generators connected directly to the grid.

It is necessary to modify the stand alone wind turbines in order to enable them to control voltage and frequency and to be able to supply power on demand and not when the wind blows.

The varying power output from the turbine has an impact on both the operation of the power system and on the power quality of the system. The stability of voltage and frequency should not be degraded significantly as the controllers of systems should to be able to prevent instability.

It is also a requirement that standard equipment is used as far as possible i.e. standard power electronic units in order to reduce cost of investment and maintenance, maximize availability of components and reduce risk of failures.

The system should also be robust and require a minimum of maintenance in order to enable it to be used in areas with a weak infrastructure.

The AC system should be able to supply power of adequate quality to standard appliances. The equipment connected to the system will be standard AC equipment of the same type as for the public grid.

The system should be able to start a grid without energy from outside and should be able to supply loads (light, TV, computers etc.) that require constant availability of the system i.e. some kind of storage or other type of generation is needed to overcome the fluctuations in the wind power and provide a satisfactory service (24hrs/7 days).

Another type of loads (space heating, refrigerators, groundwater pumps etc.) does not necessary require that the power is available constantly. These loads can be serviced when power is available to a large extend.

The system should be able to handle connection of “large” induction machines (50-75% of rated power). In small power systems the individual loads are often quite large compared to the rating of the generators. It is therefore necessary for the generators to be able to handle such situations and with adequate control of frequency and voltage in order to restore both at the specified level after a dip that is not too large.

### **1.2.2 Market experience**

In general it is considered that small wind turbines have an enormous potential in off-grid applications, particularly in isolated small grids in rural regions of developing countries. So far the market for small wind turbines is still not considered mature.

Small wind turbine domestic manufacturing and encouragement of micro-generation is expanding the market for small wind turbines (Canada, Denmark, Italy, Japan, Portugal, Spain, and the United States). Italy established net metering and reduced the minimum amount of capacity required for green certificates. In Japan, Zephyr Corporation has developed the Z-1000 Airdolphin, a small 1-kW wind turbine. The machine is being demonstrated at many sites around the world. In the UK a micro generation strategy is being implemented.

A recent study [ref 21] of the performance of 235 small wind turbines in Germany over 15 years show that small wind turbines (1 to 75 kW with a swept area < 200 m<sup>2</sup>) as expected are significantly less efficient in terms of specific power output than large grid connected wind turbines (See Figure 3 left). At the same time the cost of operating and maintaining small wind turbines is significantly larger per kWh electricity and small turbines are not competitive for grid connected applications.

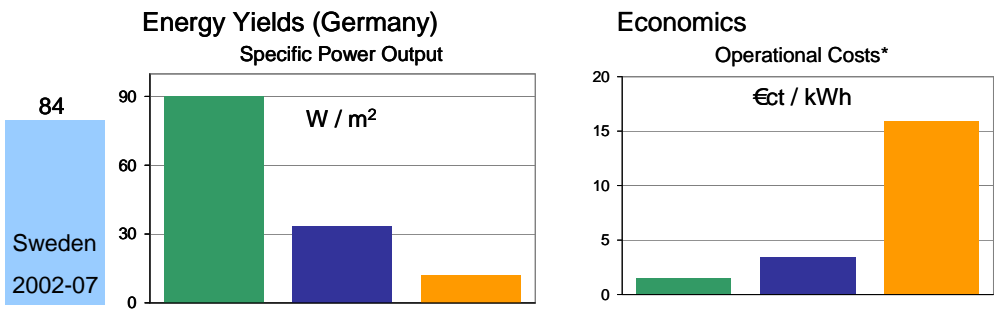


Figure 3: Specific energy yield and cost of operation and maintenance for small wind turbines compared to large wind turbines. Yellow: swept area < 40 m<sup>2</sup>; blue: 40 < swept area < 200 m<sup>2</sup>; green: large wind turbines. Source: [ref 21]

In remote applications a high technical availability of the technology is crucial to provide the needed security of supply. On the other hand the alternatives are often no power or power at a cost significantly higher than the cost of electricity is large grids. The study [ref 21] has also evaluated reliability of the small wind turbines and results show a promising low frequency of failures for the small wind turbines at a level comparable to or even lower than for large wind turbines. On the other hand the downtime associated with each failure was found to be from 2 to 25 days depending of the nature of the failure; whereas the down time for large grid connected wind turbines typically is of the order of 1-2 days and very seldom more than a week. The reason for this could be that small wind turbines are often manufactured and sold by relatively small companies with relatively few employees and very often limited or no resources allocated to service.

The costs of small (< 10 kW) stand alone turbines are typical from 3.000 €/kW and up to 10.000 €/kW.

### 1.3 Wind resource

The wind resource in Sweden is characterised by the geographical location of Sweden in a zone with generally a good wind resource and prevailing westerly

winds. In the southern part of Sweden and at the coast the wind resource is comparable to Denmark, while inland and in the northern part the wind of Sweden the wind resource is generally less attractive.

For planning purposes the wind resource is mapped by the so-called MIUU model developed by Uppsala University (Figure 4). The model is meso-scale model with a resolution of 1 km and results are presented for three heights above the displacement height: 49, 72 and 103 m. The displacement height is estimated as  $\frac{3}{4}$  the height of the trees of the forest (see section 1.4).

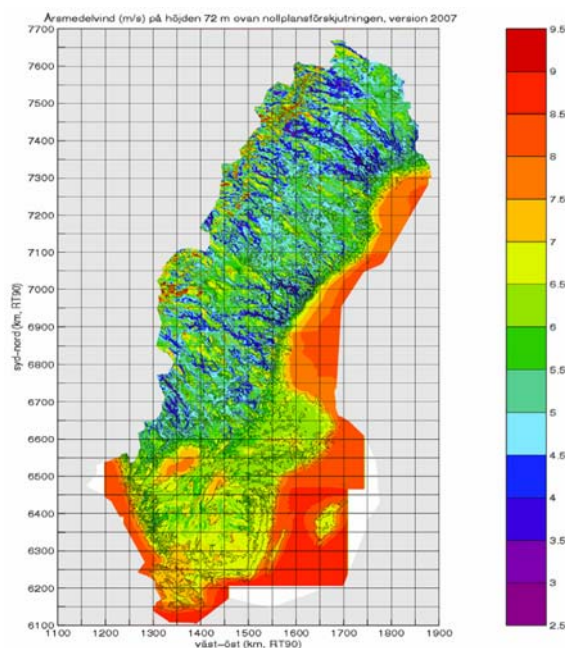


Figure 4: The meso-scale (1 km resolution) representation of the wind resource in Sweden. Source: MIUU vindkartering by Hans Bergström, Uppsala Universitet. [ ref 26 ]

## 1.4 Wind turbines in forests

Large areas of Sweden are covered by forest. In an effort to reduce visual impact from wind turbines they can be placed in forests. Strictly from a wind resource view the establishment of wind turbines in forests is less attractive compared to a location in the open countryside for three reasons: The trees mitigate the wind and reduce the available win resource, create turbulence and the prediction of the annual electricity production from a wind farm in a forest is less established.

The calculations of wind speeds over forests can be done by correcting the height of masts and wind turbines by a so-called *displacement height* depending on the density of the forest (height of the trees, the distance between them, leaves etc.) and use of a corresponding roughness as shown in Figure 5.

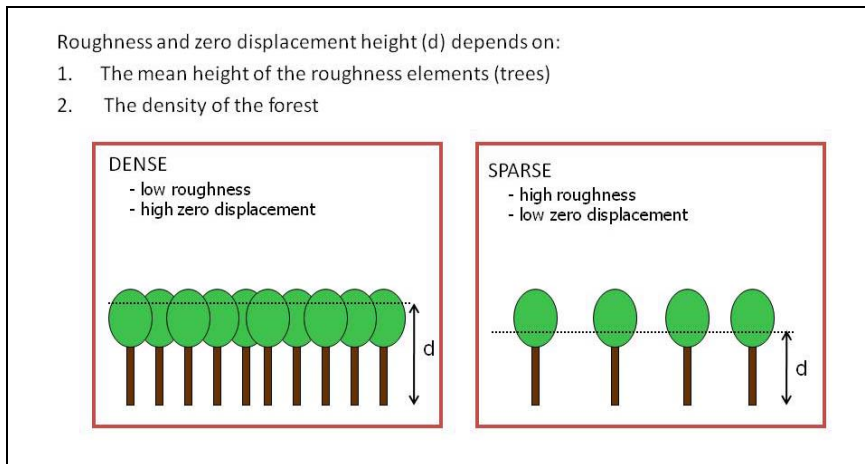


Figure 5: Displacement height and roughness in forests

To some extent it is possible to compensate for the reduced production by using higher towers of the wind turbines. However the variation of the wind with the height, the wind shear, is expected to be greater in forests and may increase the design loads on the blades (Figure 6). The effect of the wind shear and the expected increased turbulence levels in forests may influence design loads on the wind turbines and should be evaluated.

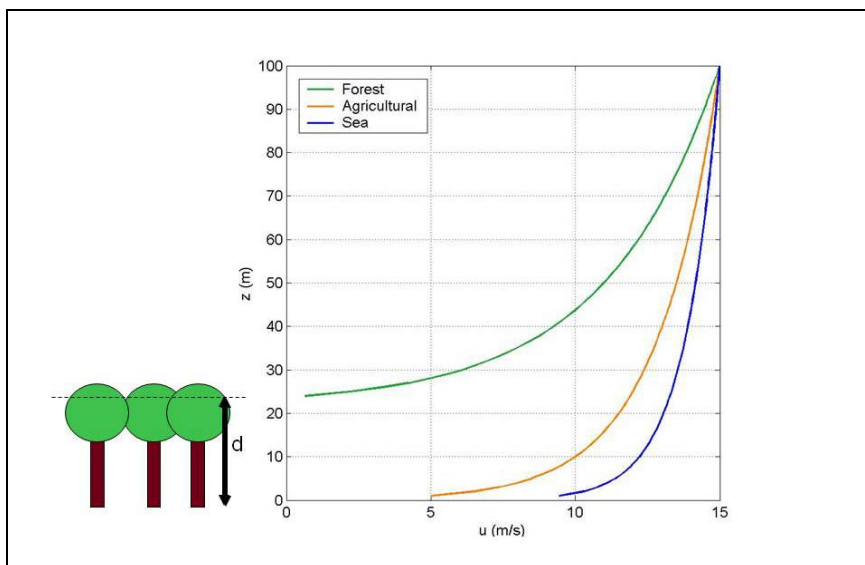


Figure 6: Vertical wind profile in a forest compared to profiles at sea and open land.

Calculations of wind speeds and annual electricity production for a specific wind turbine in a forest can for example be done using the software package WAsP<sup>2</sup> with manual correction of displacement, hub height etc. It is still subject to some

<sup>2</sup> WAsP is a software package used for predicting wind climates, wind resources and power productions from wind turbines and wind farms. The predictions are based on wind data measured at stations in the same region. The program includes a complex terrain flow model, a roughness change model and a model for sheltering obstacles. WAsP, [www.wasp.dk](http://www.wasp.dk), is developed and distributed by the [Wind Energy Department](http://www.windenergy.dk) at [Risø DTU](http://www.risoe.dk), Denmark.



uncertainty but there are continuous improvement in accordance with the current experience of studies and measures etc.

## 2 Market development

### 2.1 Introduction

Over the last 5 years the growth rate in wind energy has been very high in all continents and a considerable number of countries have very ambitious goals concerning their wind energy development. The market is maturing achieving more stable economies in the wind energy sector. Better electrical grids suited for wind power are being developed and better planning tools and other frameworks, which benefit the market for installation of wind turbines, are being implemented in all wind energy countries.

The wind power development has resulted in a dramatic increase in capacity and electrical generation from wind world wide (Figure 7). Capacity has increased from a few GW in the early 1990th to 94 GW in 2006 including 1 GW offshore wind energy.

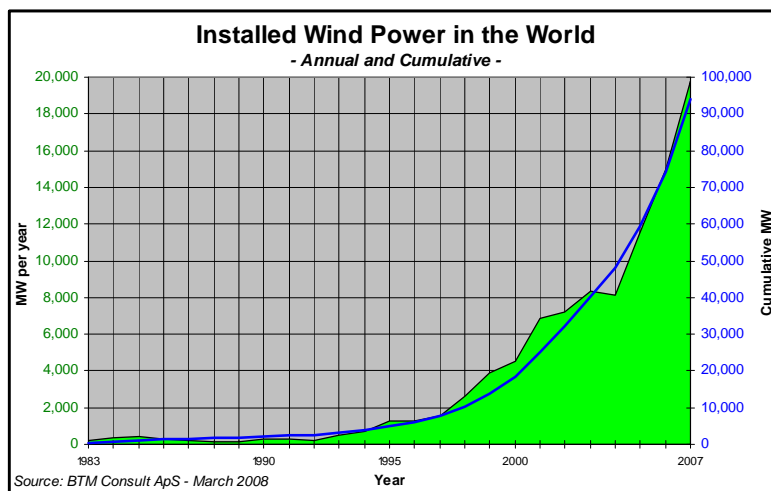


Figure 7: Annual and accumulated installed wind power capacity worldwide.  
Source: BTM Consult March 2008 [ref 1].

Nearly 20,000 MW was added alone in 2007 world wide. With an average investment of 1200 €/kW this corresponded to a total investment in wind power in 2007 of around 24 Billion €

In the 1990's there were only four to five larger 'wind energy countries' throughout the world: Denmark, US, Germany, Spain and India. Today wind turbines are installed in more than 30 countries all over the world. Since year 2000 the development primarily has taken place in Europe, but high growth rates in capacity are also seen in USA, Asia and other places in the World (Figure 8). Alone in India and China more than 4900 MW was added in 2007 bringing the accumulated capacity in Asia up to nearly 14000 MW in those two countries.

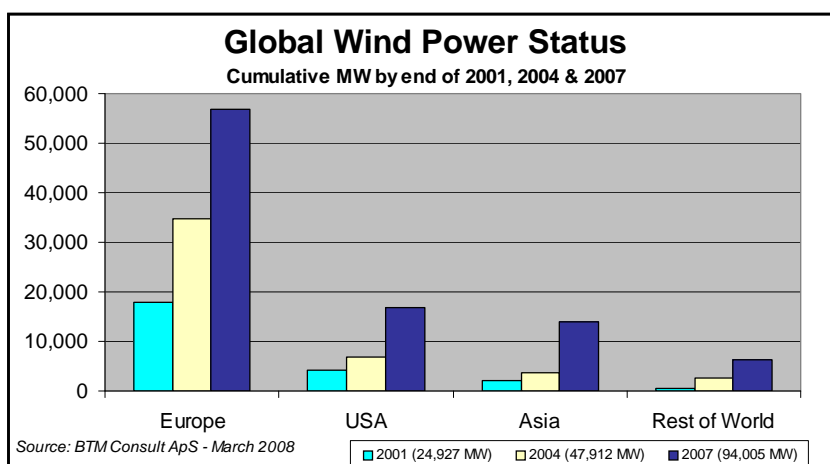


Figure 8: Global distribution of wind power developments. Source BTM Consult March 2008

As shown in Table 1 the growth in total capacity have been between 20 and 30 percent yearly over the last five years and in many countries significant amounts of capacity is in the planning stages.

Table 1: Growth in wind energy capacity from 2001 - 2006

Year:	Installed MW	Increase %	Cumulative MW	Increase %
2002	7,227		32,037	
2003	8,344	15%	40,301	26%
2004	8,154	-2%	47,912	19%
2005	11,542	42%	59,399	24%
2006	15,016	30%	74,306	25%
2007	19,791	32%	94,005	27%
<b>Average growth - 5 years</b>		<b>22.3%</b>		<b>24.0%</b>

Source: BTM Consult ApS - March 2008

### Contribution to Electrical Demand

This electrical production from wind met 1% of the total electrical demand in the World (Table 2) according to BTM [ref.1], and 1.42% of the demand in the IEA Wind member countries - up from 0.67%, and 1.2% respectively, in 2005 [ref.2]. The contribution from wind power grew only slowly because electrical demand also increased in many of the countries. Even so, the electrical output from wind in the IEA Wind member countries alone was sufficient to cover the total electricity consumption of the Netherlands.

Table 2: Development of the electricity production from wind power 1996-2006 and estimates for the next 10 years

Year	Electricity from wind power TWh*	Electricity from all power sources TWh**	Share of Wind Power %
2001	50.27	15,577	0.32
2002	64.81	16,233	0.40
2003	82.24	16,671	0.49
2004	96.50	17,408	0.55

2005	120.72	17,982	0.67
2006	152.35	18,576	0.82
2007	194.16	19,189	1.01

Source: \*BTM Consult ApS – March 2008; \*\*World Figures: IEA Energy Outlook 2006

## 1.2 Market overview

The modern age of wind energy all started in the 1980's, when there were two major but very different markets: Denmark and California, USA. In Denmark the deployment of new wind power capacity installed annually was rather constant from the year 1980 to 2000. In California, however, there was a very aggressive deployment starting 1982-83 and peaking in 1986, then followed by a sudden market collapse in 1987, due to a halt in market incentives. As a result, most of the wind turbine manufacturers in the US and abroad faced very hard times, including many bankruptcies and financial reconstructions. However, the Danish wind turbine manufacturers survived the crisis due to a fall back on their – at that time - relatively stable home market.

As of the beginning of the 1990's Germany too initiated a very dynamic development of domestic wind power, and from the middle of the 1990's to 2005 Germany has been the largest wind turbine market worldwide. Also in the mid nineties Spain initiated a very dynamic domestic market development, and in 2006 Spain was the second largest market in the world bringing them up to number 3 in the world in total installed capacity (Table 3).

Table 3: Market share in 10 leading countries

Country	2005	2006	2007	Share %	Cum. Share %
Germany	18,445	20,652	22,277	23.7%	24%
USA	9,181	11,635	16,879	18.0%	42%
Spain	10,027	11,614	14,714	15.7%	57%
India	4,388	6,228	7,845	8.3%	66%
P.R. China	1,264	2,588	5,875	6.2%	72%
Denmark	3,087	3,101	3,088	3.3%	75%
Italy	1,713	2,118	2,721	2.9%	78%
France	775	1,585	2,471	2.6%	81%
UK	1,336	1,967	2,394	2.5%	83%
Portugal	1,087	1,716	2,150	2.3%	86%
<b>Total</b>	<b>51,303</b>	<b>63,203</b>	<b>80,415</b>		
Percent of World	86.4%	85.1%	85.5%		


Source: BTM Consult ApS - March 2008

### Wind turbine manufacturers

In 2007 the six leading wind turbine manufacturers were responsible for slightly more than 85% of the entire global turn-over, measured by installed MW. Several wind turbine manufactures use sub-suppliers of major components like gearboxes and generators and for some also blades, and are mainly doing the assembling and the control systems. Towers will normally subcontracted to local manufactures. Globally we see a concentration of the production of wind turbines. Recently, however new manufacturers enter the market. This is happening in India and China as well as the USA.

Table 4 shows the 10 leading manufacturers on the world market. The table is from “World Market Up-date” [ref.1]. The table shows that Vestas is number one on the list with 22.8 % of the world market. The worlds leading manufacturers are Vestas followed by GE Wind, Gamesa, and Enercon, each of them representing about 15% of the world market. Suzlon (incl. Repower) and Siemens cover 10 and 7% of the world market, and finally Nordex, Acciona, Sinovel and Goldwind each cover about 3% of the world market.

*Table 4: The top ten manufacturers (note that the total % do not add up 100% caused by time shift between manufactures recorded sales and the recorded total installations in the world).*

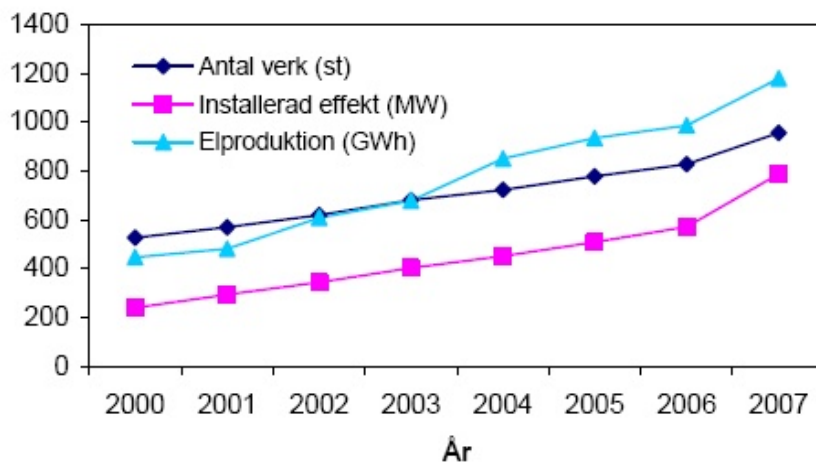
	Accu. MW 2006	Supplied MW 2007	Share 2007 %	Accu. MW 2007	Share accu. %
VESTAS (DK)	25,006	4,503	22.8%	29,508	31.4%
GE WIND (US)	9,696	3,283	16.6%	12,979	13.8%
GAMESA (ES)	10,259	3,047	15.4%	13,306	14.2%
ENERCON (GE)	11,001	2,769	14.0%	13,770	14.6%
SUZLON (Ind)	2,641	2,082	10.5%	4,724	5.0%
SIEMENS (DK)	5,605	1,397	7.1%	7,002	7.4%
ACCIONA (ES)	798	873	4.4%	1,671	1.8%
GOLDWIND (PRC)	627	830	4.2%	1,457	1.5%
NORDEX (GE)	3,209	676	3.4%	3,886	4.1%
SINOVEL (PRC)	75	671	3.4%	746	0.8%
Others	9,193	2,076	10.5%	11,269	12.0%
<b>Total</b>	<b>78,110</b>	<b>22,207</b>	<b>112%</b>	<b>100,317</b>	<b>107%</b>

Source: BTM Consult ApS - March 2008

### 2.1.1 The development in Sweden

The deployment of wind energy in Sweden has started at a modest pace (see Figure 9 and Figure 25) and at the end of 2007 Sweden has a total of 789 MW installed (963 wind turbines) of which 656 MW are land based and 133 MW located offshore (ref 1).

According to the annual operational survey (Driftuppföljning av vindkraftverk 2007; ref 25) the total electricity production from wind was 1.2 TWh in 2007 corresponding to less than 1% of the electricity consumption of Sweden. The average number of full load hours of all the wind turbines in Sweden in 2007 was 1949 i.e. only approximately 80% of the installed capacity was in operation in 2007.



*Figure 9: Development of wind energy in Sweden the last seven years [ref 40]*

### Befintliga vindkraftverk

Bilden visar de områden där det idag finns vindkraftverk.

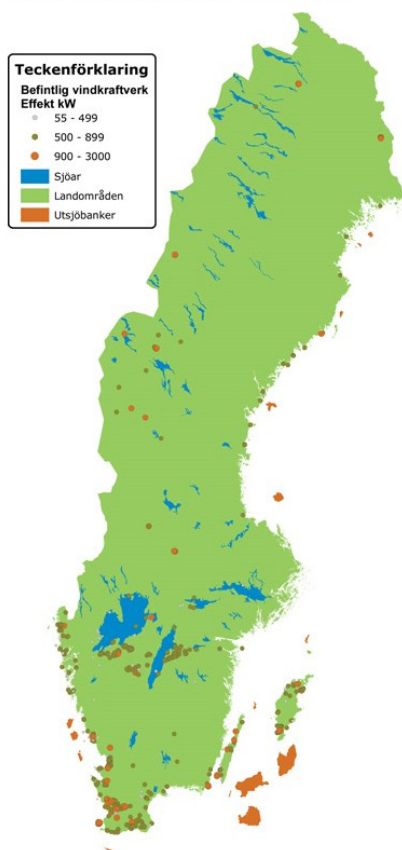


Figure 10: Location of existing wind turbines and wind farms in Sweden. Source [www.energimyndigheten.se](http://www.energimyndigheten.se). Updated 22 Feb 2008.

## 2.2 Offshore Wind – Status and Prospects

Offshore wind still only accounts for approximately 1% of the World's installed wind power capacity and the development has taken place in North European countries surrounding the North Sea and in the Baltic Sea, where around 1 GW has been installed over the last 15 years. Offshore wind is still some 50% more expensive than onshore wind (investment/MW), but due to expected benefits of more wind and a reduced visual impact from large turbines several countries have very ambitious goals concerning offshore wind.

Since the early 1990s, where the first small demonstration offshore installations of less than 5 MW were built in the Danish, Dutch and Swedish waters, offshore wind farms with a capacities above 100 MW have been erected in both Denmark, the Netherlands, Sweden and in the UK. Prospects are that the better wind resources offshore at the longer term will be able to compensate for the higher installations cost.


### Deployment

By the end of 2007, more than 1000 MW of capacity was located offshore in 4 countries: Denmark, Ireland, Netherlands, Sweden, and the United Kingdom (Table 5 and Table 6), and in 2007 110 MW at Lillgrund Sweden has been installed. Most of the capacity has been installed in relatively shallow water and close to the coast to minimize costs of foundations and sea cables and facilitate access to the wind farm.

As can be seen from Table 6 the water depth is generally less than 20 meters and within a distance to the coast of 20 km

The total capacity is still limited but growth rate has on average been 64% over the last 12 years. Offshore wind farms are installed in large units - often 100-200 MW and only two units installed a year will result in future growth rates between 20-40%. Higher costs and temporally capacity problems in the manufacturing stages and in the availability of installation vessels causes some delays at present, but still several projects in both UK and Denmark will be completed within the next 3 years.

*Table 5: Installed offshore capacity in offshore wind countries. Source BTM Consult and Danish Energy Authority*

	Installed MW 2006	Accu. MW 2006	Installed MW 2007	Accu. MW 2007
Country				
Denmark	0	397.9	0	397.9
Ireland	0	25	0	25
The Netherlands	108	126.8	0	126.8
Sweden	0	23.3	110	133.3
UK	90	304	90	394
<b>Total capacity - World</b>	<b>198</b>	<b>877</b>	<b>200</b>	<b>1077</b>

Source: BTM Consult ApS - March 2008

*Table 6: Installed offshore wind farms in the world (BTM Consult [ref.1] and Risø)*

	Turbines	Water depth in m.	Distance to coast in km.	MW	Year
Vindeby (DK)	11 x 450 kW, Bonus	2.5-5.1	2.3	4.95	1991
Lely (Ijsselmeer) (NL)	4 x 500 kW, NEG Micon	5-10	<1	2	1994
Tuno Knob (DK)	10 x 500 kW, Vestas	2.5-7.5	5-6	5	1995
Dronton (Ijsselmeer) (NL)	28 x 600 kW, NEG Micon	5	<0.1	16.8	1996
Bockstigen (S)	5 x 550 kW, NEG Micon	6	3	2.75	1997
Blyth (UK)	7 x 1.5 MW, GE Wind	6-11	<1	4	2000
Utgrunden (Oland) (S)	7 x 1.5 MW, Enron (GE)	7-10	8	10.5	2000
Middelgrunden (DK)	20 x 2 MW, Bonus	3-6	1.5-2.5	40	2000
Yttre Stengrund (S)	5 x 2 MW, NEG Micon	6-10	5	10	2001
Horns Rev (DK)	80 x 2 MW, Vestas	6-14	14-20	160	2002
Samsø (DK)	10 x 2.3 MW, Siemens	18-20	3-6	23	2002
Ronland (DK)	Mix of Vestas and Siemens	< 1	<1	17.2	2003
Frederikshavn (DK)	Mix of Vestas and Siemens	1-3	< 1	7.6	2003
North Hoyle (UK)	30 x 2 MW, Vestas	12	6-8	60	2003
Arklow Bank (UK)	7 x 3.6 MW, GE Wind	2-5	10	25.2	2003
Nysted (DK)	72 x 2.3 MW, Siemens	6-9.5	10	166	2003
Scroby Sands (UK)	30 x 2 MW, Vestas	2-8	3	60	2004
Kentish Flat (UK)	30 x 3 MW, Vestas	5	8.5	90	2005
Barrow (UK)	30 x 3 MW, Vestas	21-23	7.5	90	2006
NSW (NL)	30 x 3 MW Vestas	19-22	10	108	2006
Lillgrund (S)	48 x 2.3 MW, Siemens	3-6	7-10	110	2007
Burbo Bank (UK)	24 x 3.6 MW, Siemens	2-8	5-7	90	2007

\* Under construction

In Sweden the development offshore started already in 1990 when Sydkraft erected a single wind turbine of 220 kW approximately 250 m from the coast in 6 m deep water at Nordersund in Blekinge län. In 1997 the first small wind farm consisting of 5 wind turbines each 550 kW called Bockstigen was built near Gotland at Näsudden. In Kalmarund between Öland and mainland Sweden two wind farms Utgrunden and Yttre Stengrund are located. Recently in 2007 the first large offshore wind farm in Öresund Lillgrund 110 MW was commissioned by Vattenfall. The predicted annual Electricity production is estimated to be 400 GWh or approximately 25% of the electricity consumption of Malmö.

*Table 7: Swedish offshore projects*

	Turbines	Water depth m	Dist to coast in km.	MW	Year
Svante I	1 x 220 kW, Wind World	6	0.25	0.22	1990
Bockstigen (S)	5 x 550 kW, NEG Micon	6	3	2.75	1997
Utgrunden (Öland) (S)	7 x 1.5 MW, Enron (GE)	7-10	8	10.5	2000
Yttre Stengrund (S)	5 x 2 MW, NEG Micon	6-10	5	10	2001
Lillgrund (S)	48 x 2.3 MW, Siemens	3-6	7-10	110	2007

## 3 Cost of wind power

### 3.1 Introduction

In a European as well as a global perspective wind power is being developed rapidly. Within the past fifteen years the global installed capacity of wind power has increased from approx. 2.5 GW in 1992 to a little above 94 GW at the end of 2007, an annual growth of more than 25%. The most dominant countries in this development have been Germany, Spain and Denmark, but recently Sweden has seriously entered the scene. By now Sweden has a total capacity of almost 800 MW and a fast development wind power capacity increasing by 38% in 2007, mainly due to the installation of Lillgrund.

However, only at very few sites with high wind speeds wind power is at present economically competitive to conventional power production. This section focuses on the cost structures of a wind power plant, including the lifetime of the turbine and O&M-costs. Finally, it analyses how the costs of wind-generated power has developed in previous years and how it is expected to develop in the near future.

Wind power is used in a number of different applications, including both grid-connected and stand-alone electricity production, as well as water pumping. This section analyses the economics of wind energy primarily in relation to grid-connected turbines, which account for the vast bulk of the market value of installed turbines.

### 3.2 Cost and investment structures

The main parameters governing wind power economics include the following:

- Investment costs, including auxiliary costs for foundation, grid-connection, and so on.
- Operation and maintenance costs
- Electricity production / average wind speed
- Turbine lifetime
- Discount rate

Of these, the most important parameters are the turbines' electricity production and their investment costs. As electricity production is highly dependent on wind conditions, choosing the right turbine site is critical to achieving economic viability.

#### *Investment costs*

Capital costs of wind energy projects are dominated by the cost of the wind turbine itself (ex works)<sup>3</sup>. Table 8 shows a typical cost structure for a 2 MW turbine erected in Europe. Thus, an average turbine installed in Europe has a total investment cost of approx. 1.23 Mill. €MW, that is a 2 MW machine costs around 2.5 Mill. €including all additional costs for foundation, electrical installation, consultancy etc. The turbine's share of total cost is on average approximately 76%, while grid-connection accounts for approximately 9% and foundation for approximately 7%. The cost for acquiring the site for the turbine (land) varies significantly between projects and therefore the figure in Table 8 is only to be seen as an example. Other cost components, such as control systems and land, account for only minor shares of total costs.

*Table 8: Cost structure of a typical 2 MW wind turbine installed in Europe (year 2006 €)*

	Investment (1000 €MW)	Share (%)
Turbine (ex works)	928	75.6
Foundation	80	6.5
Electric installation	18	1.5
Grid-connection	109	8.9
Control systems	4	0.3
Consultancy	15	1.2
Land	48	3.9
Financial costs	15	1.2
Road	11	0.9
<b>Total</b>	<b>1227</b>	<b>100</b>

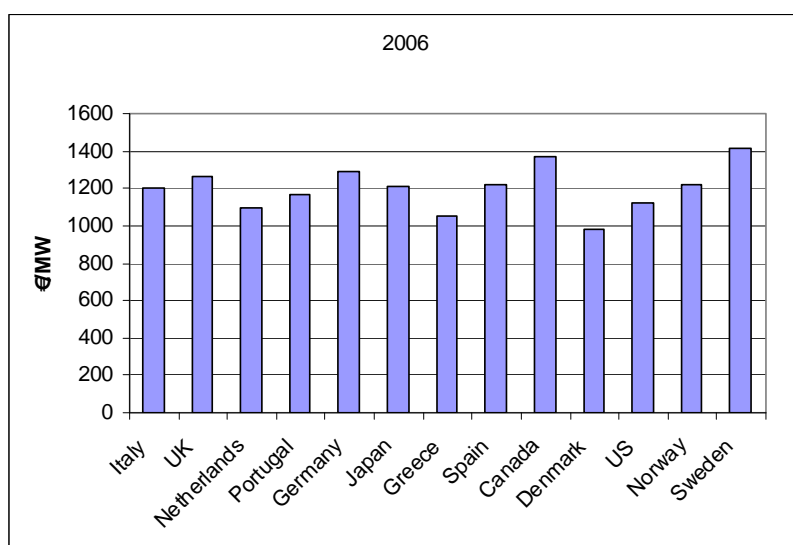
Note: Calculated by the author based on selected data for European wind turbine installations

The total cost per kW installed wind power capacity differs significantly between countries, as exemplified in Figure 11. The cost per kW typically varies from approximately 1000 €/kW to approximately 1400 €/kW. As shown in Figure 11 the investment costs per kW were found to be lowest in Denmark and approximately 5-10% higher in Greece and Netherlands. For Sweden, UK, Spain and Germany the costs found to be approximately 20 to 40% higher compared to Denmark. Though it

<sup>3</sup> 'Ex works' means that no site work, foundation, or grid connection costs are included. Ex works costs include the turbine as provided by the manufacturer, including the turbine itself, blades, tower, and transport to the site.



should be observed that Figure 11 is based on a limited number of data and therefore the results might not be representative for the mentioned countries.



*Figure 11: Total investment cost, including turbine, foundation, grid-connection etc, for different turbine sizes and countries of installation. Based on data from IEA and Elforsk rapport 08:17*

For Sweden quite a range is found in estimated investment costs, varying from approximately 1180 €/kW to approximately 1450 €/kW.

Also in the level of “other costs” as foundation, grid-connection etc. a considerable variation between countries is found in the amounts of these auxiliary costs, ranging from approximately 32% of total turbine costs in Portugal, to 24% in Germany, 21% in Italy and only 16% in Denmark, though the costs do depend not only on the country of installation but also on the size of the turbine. In general other costs are expected to be approximately 10% higher in Sweden than in Denmark owing to more difficult terrain.

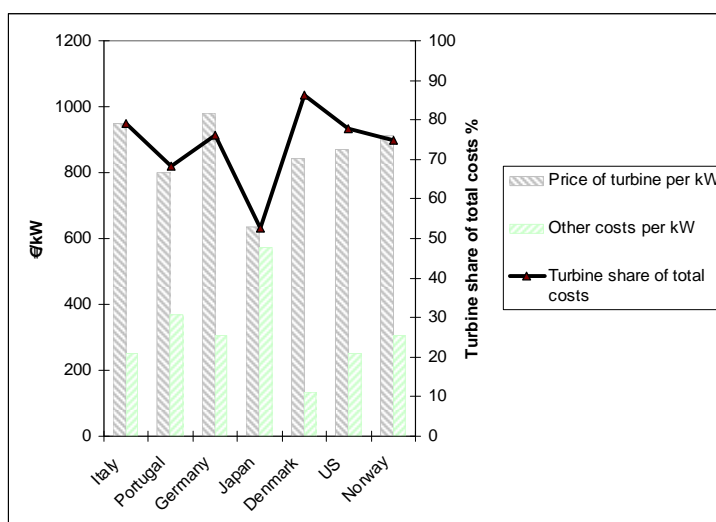
Typical ranges of these other cost components as a share of total additional costs are also shown in Table 9. In terms of variation the single most important additional component is the cost of grid-connection that in some cases can account for almost half of auxiliary costs, followed by typical lower shares for foundation cost and cost of the electrical installation. Thus these three issues might add significant amounts to total cost of the over all turbine. Cost components as consultancy and land normally account for only minor shares of additional costs.

*Table 9. Cost structure for a typically medium size wind turbine*

	Share of total cost %	Typical share of other costs, %
Turbine (ex works)	68-84	-
Foundation	1-9	20-25
Electric installation	1-9	10-15
Grid-connection	2-10	35-45
Consultancy	1-3	5-10
Land	1-5	5-10
Financial costs	1-5	5-10
Road construction	1-5	5-10

Note: Based on a limited data-selection from Germany, Denmark, Spain and UK adjusted and updated by the authors

For a number of selected countries the costs for turbine and auxiliaries (foundation, grid-connection etc.) are shown in Figure 12, below.



*Figure 12: Price of turbine and additional costs for foundation, grid-connection etc. calculated per kW for selected countries (left axes), including turbine share of total costs (right axes.)*

### *Trends influencing the costs of wind power*

In general, three major trends have dominated the development of grid-connected wind turbines in recent years:

- 1) The turbines have grown larger and taller – thus the average size of turbines sold at the market place has increased substantially.
- 2) The efficiency of the turbines' production has increased steadily.
- 3) In general, the investment costs per kW have decreased, although recent years have shown a discrepancy from this trend.

Figure 13 shows the development of the average size of wind turbines sold each year for a number of the most important wind power countries. As illustrated in Figure 13 the annual average size has increased significantly with in the last 10-15 years, from

approximately 200 kW in 1990 to 2 MW in UK in 2007, with Germany, Spain, USA and Sweden lagging only a little behind. In Sweden the size has increased gradually and by 2007 the average installed size was 1670 kW, dominated by the installation of Lillgrund. But as shown there is quite a difference between some of the countries. In India the average installed size in 2007 is approx. 1 MW, significantly below the level of UK and Germany of 2049 kW and 1879 kW, respectively. The unstable picture for Denmark in recent years mainly reflects a very small number of new turbines being installed.

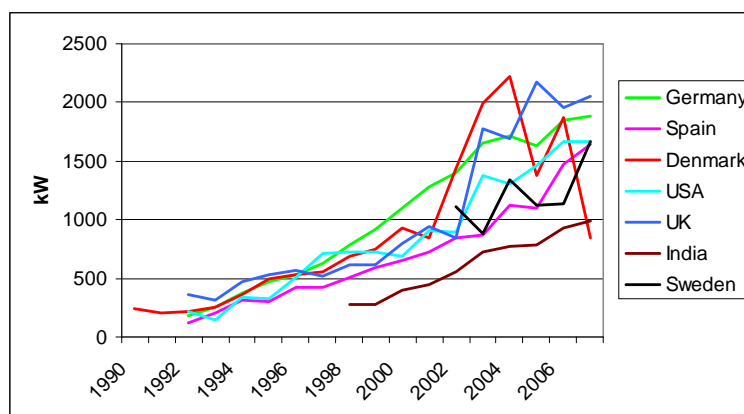


Figure 13. Development of the average wind turbine size sold in different countries.  
Source: BTM-consult

In 2007 turbines of the MW-class (i.e. above 1 MW) had a market share of more than 95%, leaving less than 5% for the smaller machines. Within the MW-segment turbines with capacities of 2.5 MW and up are getting increasingly important, even for on-land sitings. These large turbines had a share of 6% of the market in 2007, compared to only 0-0.3% at the end of 2003.

The wind regime at the chosen site, the hub height of the turbines and the efficiency of production mainly determine power production from the turbines. Thus, increasing the height of the turbines has by itself yielded a higher power production. Similarly, the methods for measuring and evaluating the wind speed at a given site have improved substantially in recent years and thus improved the siting of new turbines. In spite of this, the fast development of wind power capacity in countries such as Germany and Denmark implies that most of the good wind sites by now are taken and, therefore, new on-land turbine capacity has to be erected at sites with a marginally lower average wind speed. To this though should be added that the replacement of older and smaller turbines with new ones is getting increasingly important, especially in countries which have taken part in the wind power development for a long time as is the case for Germany and Denmark.

The development of electricity production efficiency owing to better equipment design measured as annual energy production per swept rotor area ( $\text{kWh/m}^2$ ) at a specific reference site has correspondingly improved significantly over the last years. Taking into account all the three mentioned issues of improved equipment efficiency, improved turbine siting and higher hub height the over all efficiency has increased by 2 to 3 percent annually over the last 15 years.

Figure 14 shows how investment costs have developed over the years, exemplified by the case of Denmark for the time-period 1987 to 2006. The data reflect turbines

installed in the particular year shown<sup>4</sup> and all costs at the right axis are calculated per swept rotor area, while those at the left axis are calculated per kW of rated capacity.

The number of square meters the rotor of the turbine is covering - swept rotor area - is a good proxy for the turbines' power production and therefore this measure is a relevant index for the development in costs per kWh. As shown in the figure, there has been a substantial decline in costs per unit swept rotor area in the considered period except for 2006. Thus, from the late 90s until 2004 over-all investments per unit swept rotor area have declined by more than 2% per annum during the period analysed, corresponding to a total reduction in cost of almost 30% over these 15 years. But this trend was broken in 2006 where total investment costs rose by approximately 20% compared to 2004, mainly induced by a strong increase in demand for wind turbines combined with severe supply constraints.

Looking at the cost per rated capacity (per kW), the same decline is found in the period 1989 to 2004 with the 1000 kW-machine in 2001 as the exception. The reason has to be found in the dimensioning of this specific turbine. With higher hub heights and larger rotor diameters, the turbine is equipped with a relatively smaller generator although it produces more electricity. This is particularly important to be aware of when analyzing turbines constructed to be used in low and medium wind areas, where the rotor diameter is dimensioned to be considerably larger compared to the rated capacity. As shown in Figure 14 the cost per kW-installed also rose by 20% in 2006 compared to 2004.

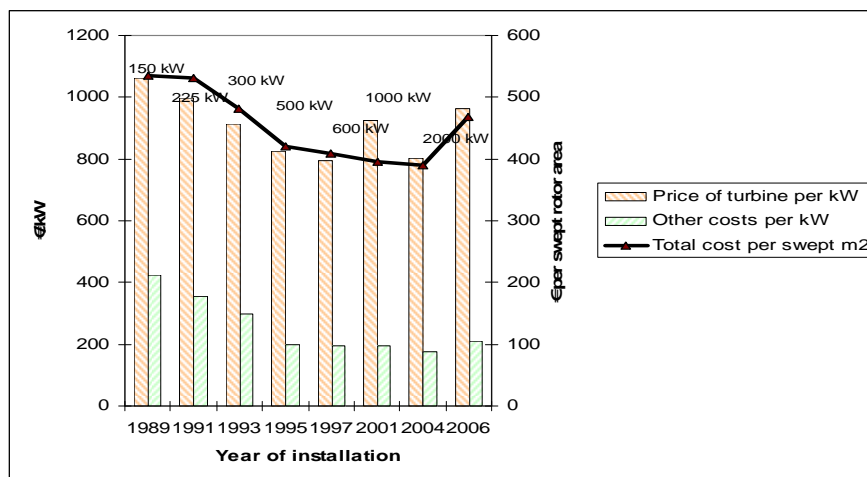


Figure 14: The development of investment costs exemplified by the case of Denmark for the time-period 1989 to 2006. Right axis: Investment costs divided by swept rotor area (€/m² in constant 2006 €). Left axis: Wind turbine capital costs (ex works) and other costs per kW rated power (€/kW in constant 2006 €).

Also, the share of other costs as a percentage of total costs has in general decreased. In 1989, almost 29% of total investment costs were related to costs other than the turbine itself. By 1997, this share had declined to approximately 20%. The trend towards lower auxiliary costs continues for the last vintage of turbines shown (2000 kW), where other costs amount to approximately 18% of total costs. But from 2004 to 2006 other costs rose almost in parallel with the cost of the turbine itself.

<sup>4</sup> All costs are converted to 2006 prices.

The recent price increases for turbines is a global phenomenon mainly stemming from a strong and increasing demand for wind power in many countries and severe constraints on the supply side, not only on the part of turbine manufacturers themselves but especially stemming from too low a production capacity of suppliers of wind turbine components. The general price increases for newly installed wind turbines in a number of selected countries are shown in Figure 15, below. As shown significant differences exist between the individual countries, price increases ranging from almost stability to a rise of more than 40%, e.g. in Sweden, US and Canada.

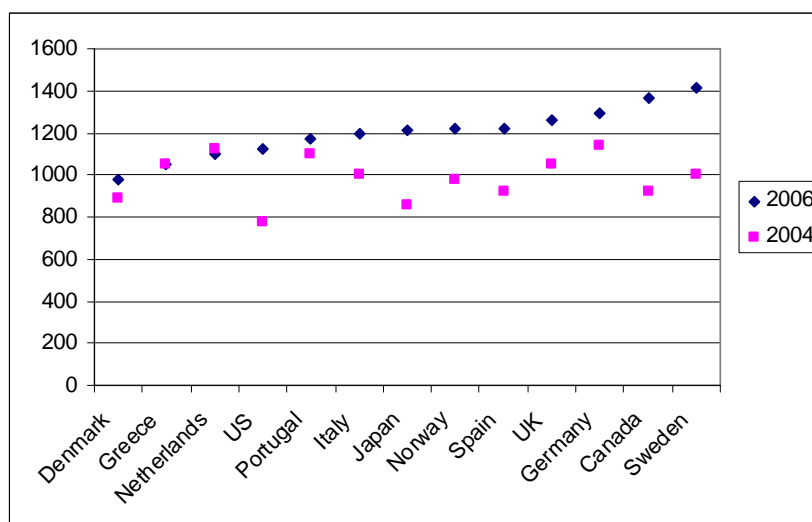


Figure 15: The increase in turbine prices from 2004 to 2006 for a selected number of countries. Source: IE and Elforsk rapport 08:17.

### 3.3 Operation and maintenance costs of wind generated power

Operation and maintenance (O&M) costs constitute a sizeable share of the total annual costs of a wind turbine. For a new turbine O&M costs might easily have an average share over the lifetime of the turbine of approximately 20-25 percent of total levelled cost per kWh produced – as long the turbine is fairly new the share might constitute 10-15 percent increasing to at least 20-35 percent by the end of the turbine's lifetime. Thus O&M costs are increasingly attracting more attention manufacturers attempting to lower these significantly by developing new turbine designs requiring fewer regular service visits and less out-time of the turbines.

O&M costs are related to a limited number of cost components:

- Insurance
- Regular maintenance
- Repair
- Spare parts
- Administration

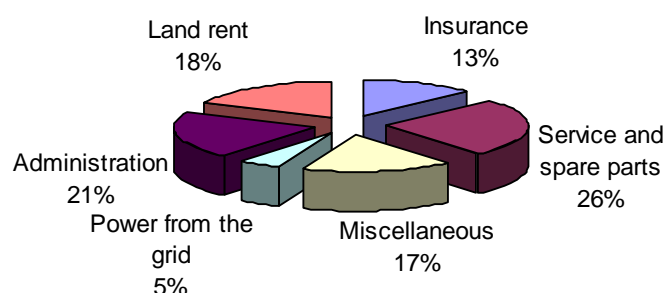
Some of these cost components can be estimated with relative ease. For insurance and regular maintenance, it is possible to obtain standard contracts covering a considerable portion of the wind turbine's total lifetime. On the other hand, costs for repair and related spare parts are much more difficult to predict. Although all cost components tend to increase with the age of the turbine, costs for repair and spare

parts are particularly influenced by turbine age, starting low and increasing over time.

Due to the newness of the wind energy industry, only a limited number of turbines have existed for the full-expected lifetime of 20 years. Of course these turbines are almost entirely small ones compared to the average size of the turbines sold at the market place nowadays and to a certain extent they have been constructed using more conservative though less stringent design criteria's than used to day. Nevertheless some experiences can be drawn from the existing older turbines but the estimates of O&M costs are still to be considered highly uncertain, especially around the end of turbines' lifetimes.

Based on the existing experiences from Germany, Spain, UK and Denmark O&M costs are in general estimated to be at a level of approximately 1.2 to 1.5 c€/kWh of produced wind power seen over the total lifetime of the turbines. Data from Spain indicate that a little less than 60% of this amount goes strictly to O&M of the turbine and the installations, split into approximately half to spare parts and the rest equally distributed onto labor costs and spare parts. The remaining 40% is almost equally split into insurance, rent of land<sup>5</sup> and overhead.

In Figure 16 is shown an average over the time-period 1997-2001 of how total O&M-costs were split into 6 different categories based on German data from Dewi. Observe that expenses for buying power from the grid and the rent of land (as in Spain) are parts of O&M-costs as calculated for Germany. For the first two years of its lifetime a turbine is normally covered by the manufacturer's warranty, thus in the German study is found fairly low total O&M-costs of 2-3% of total investment costs for these two years, corresponding to approximately 0.3-0.4 c€/kWh. After 6 years the total O&M-costs have increased to constitute a little less than 5% of total investment costs, which is equivalent to approximately 0.6-0.7 c€/kWh. These figures are fairly close in line with calculated O&M-costs for newer Danish turbines, see below.



*Figure 16: O&M-costs for German turbines distributed into different categories as an average over the time-period 1997-2001. Source: Dewi.*

<sup>5</sup> In Spain the rent of land is seen as an O&M-cost.

Figure 17 shows the total O&M-costs as found in a Danish study and how these are distributed on the different categories of O&M, according to the type, size and age of the turbine. Thus for a three year old 600 kW machine, which was fairly well represented in the study<sup>6</sup>, approximately 35% of total O&M-costs is paid for insurance, 28% for regular service, 11% for administration, 12% for repair and spare parts and, finally, 14% for other purposes. In general it is found in the study that expenses for insurance, regular service and administration were fairly stable over time, while as mentioned above the costs for repair and spare parts were heavily fluctuating. Finally, in most cases other costs were of minor importance.

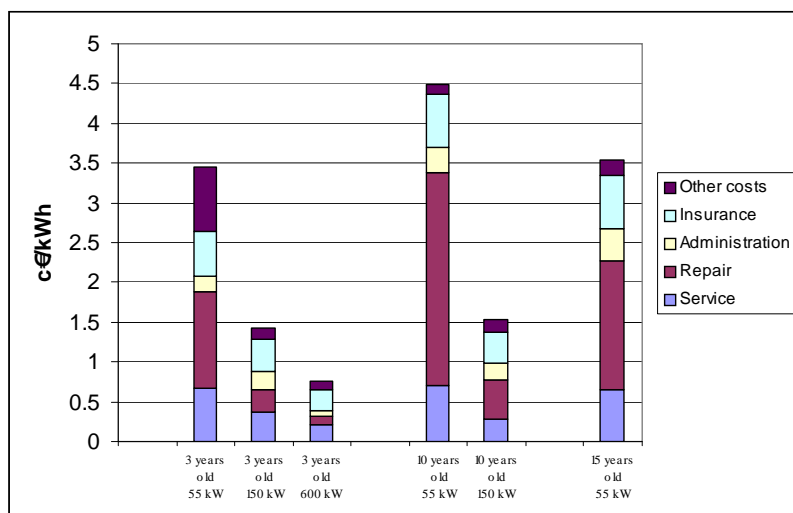


Figure 17: O&M costs as reported for selected types and vintages of turbines. Source: Jensen et al. (2002) [ref.7].

Figure 17 shows clearly the trend towards lower O&M-costs for new and larger machines. Thus for an 3-year old turbine the O&M-costs have decreased from approximately 3.5 c€/kWh for the old 55 kW turbine to less than 1 c€/kWh for the newer 600 kW machine. The figures for the 150 kW turbine are almost at the same level as the O&M-costs identified in the three countries mentioned above. Moreover, Figure 5 shows clearly that O&M-costs increase with the age of the turbines.

Though, with regard to the future development of O&M-costs care must be taken in interpreting the results of Figure 17. First, as wind turbines exhibit economies of scale in terms of declining investment costs per kW with increasing turbine capacity, similar economies of scale may exist for O&M costs. This means that a decrease in O&M-costs to a certain extent will be related to the up-scaling of the turbines. Secondly, the newer and larger turbines are more optimized with regard to dimensioning criteria's than the old ones, implying an expectation of lower lifetime O&M requirements than the older smaller turbines. But in turn this might have the adverse effect, that these newer turbines are not as robust towards unexpected events as the old ones.

<sup>6</sup> The number of observations was in general between 25 and 60.

### 3.4 The cost of energy generated by wind power

The total cost per produced kWh (unit cost) is calculated by discounting and levelling investment and O&M costs over the lifetime of the turbine, divided by the annual electricity production. The unit cost of generation is thus calculated as an average cost over the turbine's lifetime. In reality, actual costs will be lower than the calculated average at the beginning of the turbine's life, due to low O&M costs, and will increase over the period of turbine use.

The turbine's production of power is the single most important factor for the cost per generated unit of power. If a turbine is sited at a good wind location or not might totally determine if the turbine is profitable or runs with a loss. In this section the cost of wind produced energy will be calculated given a number of basic assumptions. Due to the importance of the turbine's power production this parameter will be treated on a sensitivity basis. Other assumptions include:

- The calculations are performed for a new land based medium sized turbine that is of 1.5 to 2 MW size, which could be erected today.
- Investment costs reflect the range given in section two, that is a cost per kW of 1100 to 1400 €/kW with an average of 1225 €/kW. These costs are based on data from IEA stated in 2006-prices.
- Operation and maintenance costs are assumed to be 1.45 c€/kWh as an average over the lifetime of the turbine.
- The lifetime of the turbine is set to 20 years, in accordance with most technical design criteria's.
- The discount rate is assumed to range with in an interval of 5 to 10% p.a. In the basic calculations a discount rate of 7.5% p.a. is used, though a sensitivity analysis of the importance of the above-mentioned interest range is performed.
- The economic analyses are carried out as simple national economic ones. No taxes, depreciation, risk premium etc are taken into account. Everything is calculated in fixed 2006-prices.

The calculated costs per kWh wind generated power as a function of the wind regime at the chosen sites are shown in Figure 18 below<sup>7</sup>. As shown the cost ranges from approximately 7-10 c€/kWh at sites with low average wind speeds to approximately 5-6.5 c€/kWh at good coastal positions, with an average of approximately 7c€/kWh at a medium wind site. In Europe coastal positions as these are mostly to be found at the coast of UK, Ireland, France, Denmark and Norway. Medium wind areas are mostly to be found as inland terrain in Mid- and Southern-Europe, that is Germany, France, Spain, Holland, Italy, but also as inland sites in Northern Europe in Sweden, Finland and Denmark. In many cases local conditions do significantly influence the average wind speed at the specific site for which reason strong fluctuations in the wind regime are to be expected even for neighboring areas.

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<sup>7</sup> In the figure the number of full load hours is used to represent the wind regime. Full load hours are calculated as the turbine's average annual production divided by its rated power. The higher the number of full load hours, the higher the wind turbine's production at the chosen site.



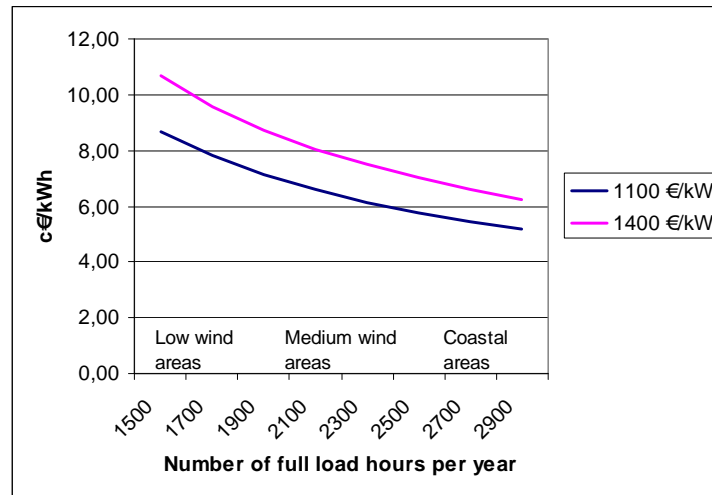


Figure 18: Calculated costs per kWh wind generated power as a function of the wind regime at the chosen site (number of full load hours). Assumptions: see text above.

Approximately 75-80% of total power production costs for a wind turbine are related to capital costs, that is costs for the turbine itself, foundation, electrical equipment and grid-connection etc. Thus a wind turbine is so called capital intensive compared with conventional fossil fuel fired technologies as a natural gas power plant, where as much as 40-60% of total costs are related to fuel and operation and maintenance costs. For this reason the costs of capital (discount or interest rate) is an important factor for the cost of wind generated power and at the same time it is a factor that varies substantially between the individual EU member countries.

In Figure 19 the costs per kWh wind produced power are shown as a function of the wind regime and the discount rate, where the last-mentioned parameter is varied between 5 and 10% p.a.

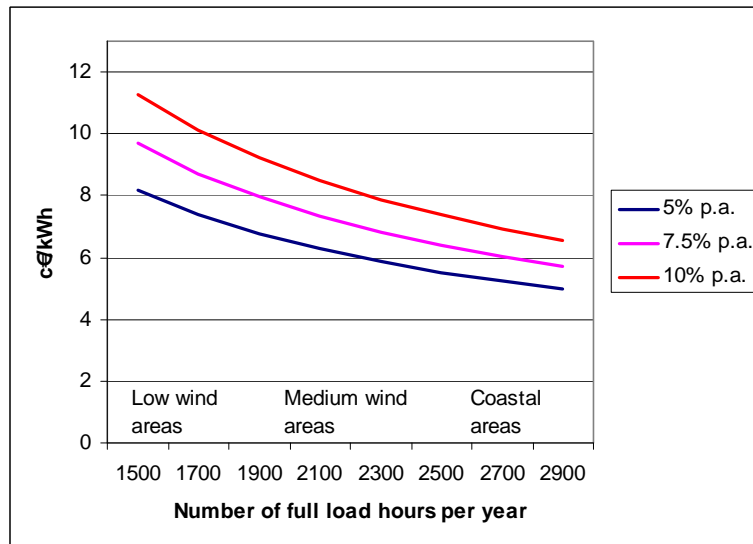


Figure 19: The costs of wind produced power as a function of wind speed (number of full load hours) and discount rate. Installed cost of wind turbines is assumed to be 1225€/kW.

As shown in Figure 19 the costs ranges between approximately 6 and 8 c€/kWh at medium wind positions, indicating that a doubling of the interest rate induces an increase in production costs of 2 c€/kWh. In low wind areas the costs are significantly higher, 8-11 c€/kWh, while the production costs range between 5 and 7 c€/kWh in coastal areas.

### 3.5 Development of the cost of wind generated power

The rapid European and global development of wind power capacity has had a strong influence on the cost development of wind power with in the past 20 years. To illustrate the trend towards lower production costs of wind generated power, a historical case showing the production costs for different sizes and vintages of turbines is constructed. Due to limited data the trend curve been only been constructed for Denmark, though a similar trend was observed in Germany at a little lower pace.

Figure 20 shows the calculated unit cost for different sizes of turbines based on the same assumptions as used in the previous section. Thus a 20-year lifetime is assumed for all turbines in the analysis and a real discount rate of 7.5% p.a. is used. All costs are converted into constant 2006-prices. The turbines' electricity production is estimated for two wind regimes, a coastal and an inland medium wind position, respectively. The starting point for the analysis is the 95 kW machine that mainly was installed in Denmark in the mid 80s, followed by successively newer turbines (150 kW, 225 kW etc.) and ending by the newest in the analysis, the 2000 kW turbine typically installed from around year 2003 and onwards. It should be noted that wind turbine manufacturers, as a rule of thumb, expects the production cost of wind power to decline by 3-5% for each new turbine generation they add to their product portfolio. Do observe that the calculations are performed for the total lifetime (20 years) of the turbines, which means that calculations for the old turbines are based on track records of more than 15 years (average figures), while newer turbines might have a track record of only a few years. Thus the newer the turbine the more uncertainty is related to the calculations.

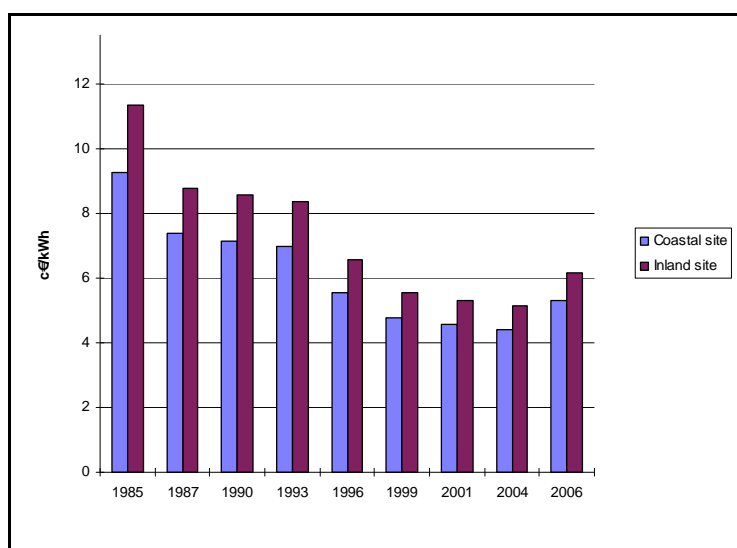


Figure 20: Total wind energy costs per unit of electricity produced, by turbine size. (c€/kWh, constant 2006 prices).

In spite of this Figure 20 clearly illustrates the economic consequences owing to the trend towards larger turbines and improved cost-effectiveness. For a coastal position, for example, the average cost has decreased from approximately 10.1 c€/kWh for the 95 kW turbine (mainly installed in the mid 80s) to approximately 5.3 c€/kWh for a fairly new 2000 kW machine, an improvement of almost 50 percent over a time span of 20 years (constant 2006 prices).

### 3.6 Future development of the cost of wind generated power

In this section the future development of the economics of wind power is illustrated by the use of the experience curve methodology. The experience curve approach was developed back in the 70s of the Boston Consulting Group and the main feature is that it relates the cumulative quantitative development of a product with the development of the specific costs. Thus, if the cumulative sale of a product is doubled, the estimated learning rate tells you the achieved reduction in specific product costs.

The experience curve is not a forecasting tool based on estimated relationships. It is merely pointing out to you, that if the existing trends are going to continue in the future, then we might see the proposed development. It converts the effect of mass production into an effect upon production costs, other casual relationships not taken into account. Thus changes in market development and/or technological breakthroughs within the field might considerably change the picture.

In a number of projects different experience curves have been estimated<sup>8</sup>, but unfortunately also mostly using different specifications, which means that not all of these can be directly compared. To get the full value of the experiences gained not only the price reduction of the turbine (€/KW-specification) should be taken into account, but the improvements in efficiency of the turbine's production as well. The last mentioned issue requires the use of an energy specification (€/kWh), which excludes many of the mentioned estimations, leaving mainly [ref 8] and [ref 9]. Thus using the specific costs of energy as a basis (costs per kWh produced) the estimated progress ratios in these publications range from 0.83 to 0.91, corresponding to learning rates of 0.17 to 0.09. That is when total installed capacity of wind power is doubled the costs per produced kWh for new turbines are reduced between 9 and 17%. In this way both the efficiency improvements and embodied and disembodied cost reductions are taken into account in the analysis.

Wind power capacity has developed very rapidly in recent years, on average by 25-30% per year during the last ten years. Thus at present the total wind power capacity is doubled approximately every 3rd to 4th year. In Figure 21 below are shown the consequences for wind power production costs according to the following assumptions:

- The present price-relation is expected to be kept until year 2010; that is no price reductions are foreseen in this period due to a persistent strong demand after new wind turbine capacity and severe sub-suppliers constraints in delivery of turbine components.

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<sup>8</sup> See for instance [ref 8], [ref 9] and [ref11]

- From 2010 and until 2015 a learning rate of 10 % is assumed, implying that each time the total installed capacity is doubled then the costs per kWh wind-generated power is reduced by 10%.
- The growth rate of installed capacity is assumed to double cumulative installations each 3rd year.
- The curve illustrates cost development in Denmark, which is a fairly cheap wind power country. Thus the starting point for the development is a cost of wind power of approx. 6.1 c€/kWh for an average 2 MW turbine, sited at a medium wind regime (average wind speed of 6.3 m/s at a hub height of 50 m). Alternatively, the development for a coastal position is also shown.

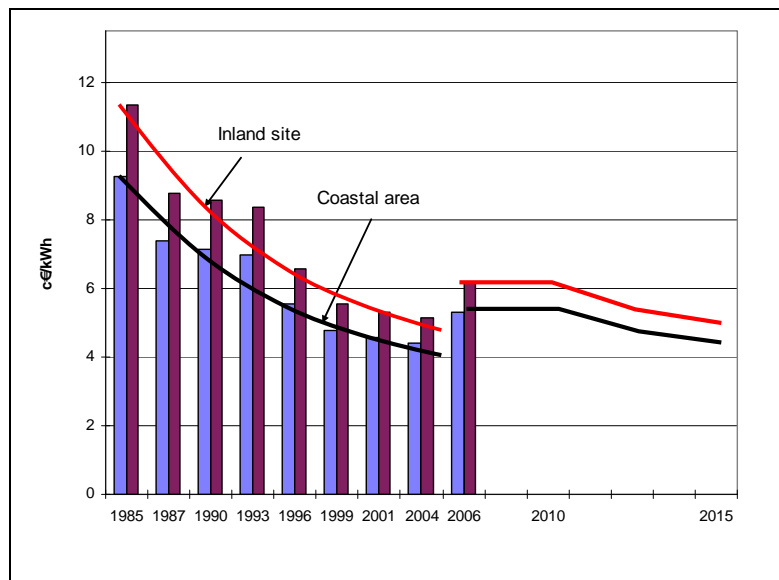


Figure 21: Using experience curves to illustrate the future development of wind turbine economics until 2015. Costs illustrated for an average 2MW turbine installed either at a inland site or at a coastal position.

At present the production costs for a 2 MW wind turbine installed in an area with a medium wind speed (inland position) is approximately 6.1 c€/kWh wind produced power. If sited at a coastal position costs today are approx. 5.3 c€/kWh. If a doubling time of total installed capacity of three years is assumed the cost interval would in 2015 be approximately 4.3 to 5.0 c€/kWh for a coastal and inland site, respectively. A doubling time of five years, would imply a cost interval in 2015 of 4.8 to 5.5 c€/kWh. As mentioned Denmark is a fairly cheap wind power country. For more expensive countries the cost of wind power produced will increase by 1- 2 c€/kWh.

## 4 Offshore development

### 4.1 Development and investment costs of offshore wind power

Offshore wind only counts for a small amount of total installed wind power capacity – approx. 1% - and development has mainly taken place in North European counties mainly round the North Sea and the Baltic Sea, where by now a little more than 20 projects have been implemented. At the end of 2006 almost 900 MW of capacity was located offshore in five countries: Sweden, Denmark, Ireland, Netherlands and the

United Kingdom as shown in Table 10. Most of the capacity has been installed on relatively low water depth (below 20 m) and with a proximity to the coast of no more than 20 km to keep the extra cost to foundations and sea cable as low as possible. In 2007 the Swedish offshore wind farm Lillgrund with a rated capacity of 110 MW was installed, increasing the Swedish offshore capacity to 133 MW.

Offshore wind is still some 50% more expensive than onshore wind, but due to expected benefits of more wind and lesser visual impact from larger turbines several countries have very ambitious goals concerning offshore wind.

The total capacity is still limited but growth rates are high. Offshore wind farms are installed in large units - often 100-200 MW - and only two units installed a year will result in future growth rates between 20-40%. Higher costs and temporary capacity problems in the manufacturing stages and in availability of installation vessels causes some delays at present, but still several projects in both UK, and Denmark will be finished within the next 3 years.

*Table 10: Installed offshore capacity in offshore wind countries. Source BTM Consult*

Country	MW Installed in 2006	Accumulated MW end 2006	MW Installed in 2007	Accumulated MW end 2007
Denmark	0	398	0	398
Ireland	0	25	0	25
The Netherlands	108	127	0	127
Sweden	0	23	110	133
UK	90	304	90	394
Total in the world	198	877	200	1077

Offshore costs are largely dependent on weather and wave conditions, water depth, and distance to the coast. The most detailed cost information on recent offshore installations comes from the UK where 90 MW was added in both 2006 and 2007 and from Sweden with the installation of Lillgrund in 2007. Table 11 gives information on some of the recently established offshore wind farms.

As shown in Table 11 the chosen turbine size for offshore wind farms ranges from 2 MW to 3.6 MW, the newer wind farms equipped with the larger turbines. Also the turbine farm sizes differ substantially from the fairly small Samsø wind farm of 23 MW to Robin Rigg with a rated capacity of 180 MW, which will be the world's largest offshore wind farm. Investment costs per MW range from a low of 1.2 mill.€/MW (Middelgrunden) to almost the double of 2.7 mill.€/MW (Robin Rigg) cf. Figure 22.

*Table 11: Key information on recent offshore wind farms. (Note that Robin Rigg is planned to be in operation in 2008)*

	In operation	Number of turbines	Turbine size	Capacity MW	Investment cost mill. €
Middelgrunden (DK)	2001	20	2	40	47
Horns Rev I (DK)	2002	80	2	160	272

Samsø (DK)	2003	10	2.3	23	30
North Hoyle (UK)	2003	30	2	60	121
Nysted (DK)	2004	72	2.3	165	248
Scroby Sands (UK)	2004	30	2	60	121
Kentich Flat (UK)	2005	30	3	90	159
Barrows (UK)	2006	30	3	90	-
Burbo Bank (UK)	2007	24	3.6	90	181
Lillgrund (S)	2007	48	2.3	110	197
Robin Rigg (UK)	2008	60	3	180	492

The higher capital costs of offshore are due to the larger structures and complex logistics of installing the towers. The costs of offshore foundations, construction, installations, and grid connection are significantly higher than for onshore. For example, typically, offshore turbines are 20% more expensive, and towers and foundations cost more than 2.5 times the price for a project of similar size onshore.

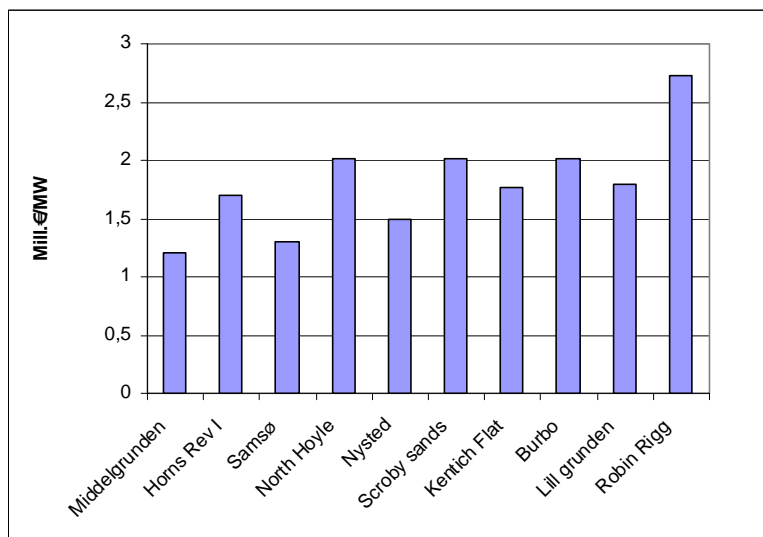


Figure 22: Investments in offshore wind farms, mill.€/MW (Current prices)

In general the costs of offshore capacity have increased in recent years as seen for on land turbines and these increases are only partly reflected in the costs shown above in Figure 22. For that reason average cost of future offshore farms will expectedly be higher. Lillgrund is seen to be at the lower end of the cost range, which to some extent may be due to that this offshore plant was contracted before prices really started to rise. On average investment costs for a new offshore wind farm today are expected be in the range of 2.0 to 2.2 mill. €/MW for a near-shore shallow depth facility

To illustrate more thoroughly the economics of offshore wind turbines, the two largest Danish offshore wind farms together with the Swedish Lillgrund are chosen as examples. The Horns Rev project located approximately 15 km off the west coast of Jutland (west of Esbjerg) was finished in 2002. It is equipped with 80 2 MW machines and thus have a total capacity of 160 MW. The Nysted offshore wind farm is located south of the isle of Lolland. It consists of 72 2.3 MW turbines and have a total capacity of 165 MW. Both wind farms have their own transformer station located at the sites, which through transmission cables are connected to the high

voltage grid at the coast. The farms are operated from onshore control stations and no staff is required at the sites.

Lillgrund is located south of the Øresund-bridge connecting Copenhagen and Malmö approximately 8-10 km off the Swedish coast. Lillgrund is equipped with 48 2.3 MW turbines. The average investment costs related to the above mentioned wind farms are shown in Table 12 split into main components.

*Table 12: Average investment costs per MW related to offshore wind farms at Horns Rev, Nysted and Lillgrund.*

	Horns Rev and Nysted		Lillgrund	
	Investments 1000 €/MW	Share %	Investments 1000 €/MW	Share %
Turbines ex work, including transport and erection	872	49	1074	57
Trafostation and main cable to coast	289	16	244	13
Internal grid between turbines	91	5	-	-
Foundations	375	21	361	19
Design, project management	107	6	60	3
Environmental analysis etc.	54	3	-	-
Other Contractors	-	-	80	4
Miscellaneous	11	<1	54	3
<b>Total</b>	<b>1798</b>	<b>~100</b>	<b>1873</b>	<b>~100</b>

*Note: 2007-prices. Horns Rev/Nysted recalculated to 2007-prices. Exchange rate 1 € = 7.45 DKK=9.31 SEK*

In Denmark all of the above costs components have to be born by the investors except the costs of the transformer station and the main transmission cable to the coast, which is born by the TSO's in the respective areas. The total cost of each of the two offshore farms is close to 260 mill. €

Compared to land-based turbines the main differences in the cost structure are related to two issues [ref.15]:

- Foundations are considerably more costly for offshore turbines. The costs depend on both the sea depth, and the chosen principle of construction<sup>9</sup>. For a conventional turbine sited on land, the share of the total cost for the foundation normally is approx. 5-9%. As an average of the three above mentioned projects this percentage is 20% (cf. Table 12), and thus considerably more expensive than for on-land sites. But it should be kept in mind that considerable experiences are gained in establishing these two wind farms and therefore a further optimization of foundation can be expected in future projects.
- Transformer station and sea transmission cables. Connections between the turbines and to the centrally located transformer station and from thereon to the coast generate additional costs compared with on-land sites. For Horns Rev, Nysted and Lillgrund wind farms the average cost share for the transformer station and sea transmission cables is between 13 and 21% (cf. Table 12). For

<sup>9</sup> At Horns Rev mono-piles have been used, while the turbines at Nysted are erected on concrete foundations.

Horns Rev and Nysted a minor share of this amounting to 5% is related to the internal grid between turbines.

Finally, in relation to Horns Rev and Nysted a number of environmental analysis, including an environmental impact investigation and visualizing the wind farms, and also additional research and development were carried out. The average cost share for these analyses for the two wind farms account for approximately 6% of total costs, but part of these costs are related to the pilot character of these projects and is not expected to be repeated next time an offshore wind farm will be established.

## 4.2 The cost of energy generated by offshore wind power

Though the costs are considerable higher for offshore wind farms this is to a certain degree moderated by a higher total electricity production from the turbines due to higher offshore wind speeds. For an on-land installation utilization time is normally around 2000-2300 hours per year, while a typical offshore installation has an utilization time of 3000 hours per year or above. The investment and production assumptions used to calculate the costs per kWh are stated in Table 13.

*Table 13: Assumptions used for economic calculations. Note that Robin Rigg is expected to be in operation in 2008.*

	In operation	Capacity MW	Mill.€MW	Full load hours per year
Middelgrunden	2001	40	1.2	2500
Horns Rev I	2002	160	1.7	4200
Samsø	2003	23	1.3	3100
North Hoyle	2003	60	2.0	3600
Nysted	2004	165	1.5	3700
Scroby sands	2004	60	2.0	3500
Kentich Flat	2005	90	1.8	3100
Burbo	2007	90	2.0	3550
Lillgrund	2007	110	1.8	3000
Robin Rigg	2008	180	2.7	3600

**In addition the following economic assumptions are used:**

- Over the lifetime of the wind farm annual operation and maintenance costs are assumed to 16 €/MWh, except for Middelgrunden where O&M costs based on existing accounts are assumed to be 12 €/MWh for the entire lifetime. These assumptions on O&M-costs are subject to high uncertainty.
- The number of full load hours is assumed for a normal wind year, corrected for shadow effects in the farm and for unavailability and losses in transmission to the coast.
- The balancing of the power production from the turbines is normally the responsibility of the farm owners. According to previous Danish experiences



balancing requires an equivalent cost of approx. 3 €/MWh. Also balancing costs are subject to high uncertainty and might differ substantially between countries.

- The economic analyses are carried out as simple national economic ones, using a discount rate of 7.5% p.a. over the assumed lifetime of 20 years. No taxes, depreciation, risk premium etc are taken into account.

Figure 23 shows the total calculated costs per MWh for the wind farms stated in Table 14.

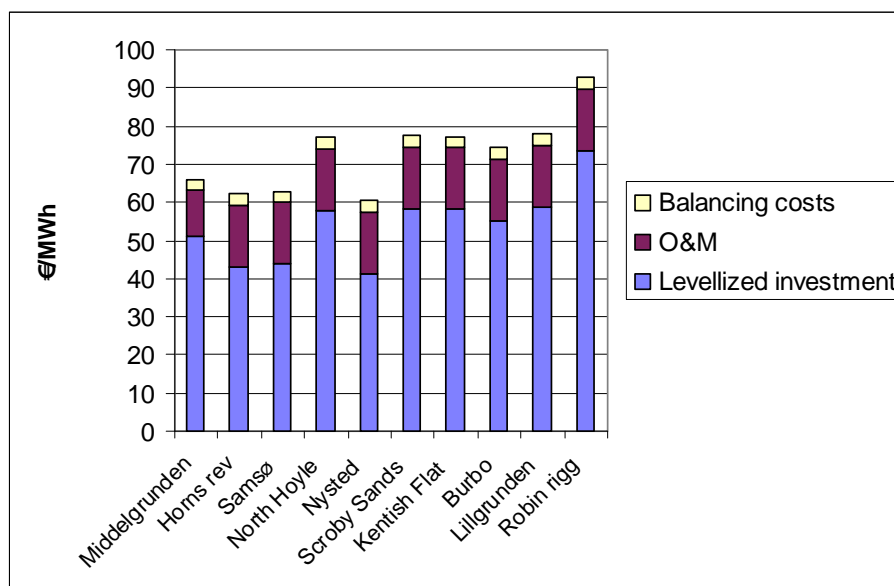


Figure 23: Calculated production cost for selected offshore wind farms, including balancing costs (2006-prices).

As shown in Figure 23 total production costs differ significantly between the illustrated wind farms, Horns Rev, Samsø and Nysted being among the cheapest, while especially Robin Rigg in UK appears to be expensive. Lillgrund is at approximately the same level as the recent British offshore wind farms, Scroby Sands, Kentish Flat and Burbo. Partly differences can be related to depth of sea and distance to shore, partly to increased investment costs. Observe that O&M-costs are assumed to be at the same level for all wind farms (except Middelgrunden) and are subject to considerable uncertainty.

Costs are calculated as simple national economic ones, thus these costs will not be those of a private investor, which will have higher financial costs, require a risk premium and a profit. How much a private investor will add on top of the simple costs will among other things depend on the perceived technological and political risk of establishing the offshore farm and, on the competition between manufacturers and developers.

### 4.3 Development of the cost of offshore wind power until 2015

Until 2004 the cost of wind turbines in general followed the development of a medium-term cost reduction curve (learning curve) showing a learning rate of approximately 10% that is each time wind power capacity was doubled the cost was reduced by approx. 10% per MW-installed. This decreasing cost-trend was

interrupted in 2004-6 where the price of wind power in general increased by approx. 20-25%, mainly caused by increasing material costs and a strong demand for wind capacity implying scarcity not only of wind power manufacturing capacity but also of sub supplier capacity for manufacturing turbine components.

A similar increase in price is witnessed for offshore wind power, although a fairly small number of realized projects in combination with a large spread in investment costs make it difficult exactly to identify the price level for offshore turbines. On average expected investment costs for a new offshore wind farm will today be in the range of 2.0 to 2.2 mill.€MW.

In the following the medium term cost development of offshore wind power will be estimated using the learning curve methodology. However, it should be kept in mind that considerable uncertainty is related to the use of learning curves even for the medium term and results should be used with caution.

The medium term cost perspectives for offshore wind power is shown in Table 14 given the following conditions:

- The existing manufacturing capacity constraints for the wind turbines will persist until 2010. Although we gradually will see an expanding industrial capacity for wind power, a continued increasing demand will also continue to strain the manufacturing capacity and not before 2011 increasing competition among wind turbine manufacturers and sub suppliers will again imply unit reduction costs in the industry.
- The total capacity development of wind power is assumed to be the main driving factor also for the cost development of offshore turbines, because the major part of turbine costs are related to the general wind power industry development. Thus, the growth rate of installed capacity is assumed to double cumulative installations each 3rd year.
- For the period 1985 to 2004 a learning rate of approx. 10% was estimated [ref. 15]. With the return of competition in the wind industry again in 2011 this learning rate is again expected to be realized by the industry in the time period until 2015.

Given these assumptions minimum, average and maximum cost-scenarios are reported in Table 14

*Table 14: Estimates for cost development of offshore wind turbines until 2015, constant 2006-€.*

	Investment costs, Mill. €MW			O&M	Cap. factor
	Min	Average	Max	€MWh	%
2006	1.8	2.1	2.4	16	37.5
2015	1.55	1.81	2.06	13	37.5

As shown in Table 14 average cost of offshore wind capacity is calculated to decrease from 2.1 mill.€MW in 2006 to 1.81 mill€MW in 2015 or by approx. 15%. A considerable spread of costs will still exist, from 1.55 mill. €MW to 2.06 mill.€MW. A capacity factor of constant 37.5% (corresponding to a number of full load hours of approx. 3300) is expected for the whole period, covering an increasing production from newer and larger turbines moderated by sites with lower wind regimes and increasing distance to shore and thus increasing losses in transmission of power.

A study made in UK [ref.2] has estimated the future costs of offshore wind generation and the potential for cost reductions. It identified the cost of raw materials - especially steel, which accounts for about 90% of the turbine and is a primary cost driver. The report emphasized that major savings can be realized if turbines are made of lighter, more reliable materials and if major components are developed to be more fatigue resistant. A cost model based on 2006 costs predicted that costs will rise from approximately 1.6 million £/MW to approximately 1.75 million £/MW (2.37 to 2.6 million €/MW) in 2011 before falling by around 20% of the cost by 2020.

## 5 Policy and planning

### 5.1 National CO<sub>2</sub> benefits and targets

All countries recognize the need to reduce carbon emissions and maintain that renewable energy in general offer great potential to reduce overall carbon emission of the power industry. In addition, reducing the cost and security issues of using imported fuels is an element of several national targets. Establishing various types of national objectives or targets is used to define goals, develop policies, measure progress, and revise policies and goals as needed along the way.

Several types of targets are set in the IEA Wind member countries. Renewable energy targets have been set e.g. by Australia, Denmark, Finland, Germany, Ireland, Italy, the Netherlands, Sweden, and the United Kingdom. Wind generating capacity (MW) or production (MWh) targets for a certain year has been established in e.g. Greece, Japan, Republic of Korea, Norway, Spain and Switzerland. Although targets are popular, Canada, and the United States have rapidly growing installed capacity without the benefit of official targets.

An important contributor to the growth of the European market for wind energy technology has been EU framework legislation combined with legislation at the national level, aimed at reducing barriers to the development of wind energy and other renewables. The new binding EU target is that 20% of Europe's energy should be provided by renewables in 2020. There is a specific sectoral target for biofuels of 10% by 2020, but no target for renewable electricity or individual technologies such as wind power.

The binding target for renewable energy in Sweden is proposed to be 49% of the final energy consumption in 2020 compared to 39.8% in 2005.

#### 5.1.1 National Incentive Programs

Table 15 below show the most used incentives in IEA Member countries related to investment, production and market [ref.2]

*Table 15. Incentive programs offered in some IEA member countries. [ref 2]  
(NDA means no data available).*

		Australia	Canada	Denmark	Finland	Germany	Greece	Ireland	Italy	Japan	Korea	Mexico	Netherlands	Norway	Portugal	Spain	Sweden	Switzerland	United Kingdom	United States
Investment Support	Direct capital investment subsidies/ grants		X		X		X	NDA	X	X	X			X	X	X			X	X
	Capital investment write-offs		X					NDA				X	X							
	Soft loans							NDA			X		X							X
	Others							NDA	X											
Production Support	Premium price for generation		X	X		X	X	NDA	X		X		X		X	X		X	X	
	Exemption from energy taxes				X			NDA									X		X	
	Production tax credits							NDA												X
	Others		X					NDA	X		X	X								X
Demand Creation	Obligation for production from renewables on suppliers	X	X					NDA	X	X						X	X		X	X
	Free market for green electricity				X			NDA	X				X		X	X		X		X
	Others					X	X	NDA			X									
Total																				

## Capital Investment

Incentive programs that help offset the capital cost of wind farm development to varying degrees have been successful in several countries. Programs range from direct investment subsidies of 30- 50 %, over subsidies to different part of projects to subsidies to installation costs for demonstration projects.

## Production Subsidies

Price incentives (feed-in tariffs) are paid to operators according to the amount of electrical generation of the wind project, thus rewarding productivity. Tariffs can also be used to promote specific national goals and have stimulated wind farm development in several countries.

In some countries, the premium price for renewable electricity is reduced in future years and policy audits are included in the laws.

Changing the rules governing subsidies can have dramatic effects on the wind energy market. E.g. has stop and go effects been a negative experience in several countries.

## Demand creation

Many national and state governments require utilities to purchase a percentage of their overall generating capacity from renewable resources. Wind energy is the preferred option by most utilities to satisfy this obligation. Also wind energy qualifies as green electricity to meet utility purchase obligations, to be traded as certificates, or to meet consumer preferences.

## Other Support Mechanisms

Other kinds of support have accelerated the development of wind energy in the IEA Wind member countries. For example comprehensive Wind Energy Atlas that allows planners of wind energy projects to generate a detailed picture of wind patterns for any location. And in Germany and Denmark, Federal authorities have identified

suitable areas for offshore wind farms in the North Sea and Baltic Sea, making planning easier for investors.

### 5.1.2 Benefits to national turnover and employments

The economic impact of wind energy is reported in various ways by the IEA Wind member countries (Table 16). One measure, sometimes referred to as economic turnover or contribution to gross domestic product, is the value of all economic activity related to such development. It includes payments to labour, cost of materials for manufacture and installation, transportation, sales for export, and value of electricity generated. Other values reported include industrial activity, construction, and value of exports. More countries than ever are estimating the number of jobs created by wind energy manufacturing, development, and operation. The economic impact of wind energy development is reported in various ways by the IEA Wind member countries.

*Table 16: Installed wind capacity in relation to jobs and economic impact. [ref 2] IEA Wind annual report 2006*

<b>Table 6 Capacity in relation to estimated jobs and economic impact in 2006</b>				
Country	Capacity (MW)	Estimated number of jobs	Economic impact (Million EURO)	
Germany	20,622	70,000	turnover	5,650
Spain	11,615	35,000	nda	
United States	11,575	10,000+	new capacity investment	3,030
Denmark	3,137	26,000*	turnover**	5,100
Italy	2,123	4,500	turnover	500
United Kingdom	1,963	4,000+	turnover	965
Portugal	1,698	nda	nda	
Japan	1,574	nda	nda	
Netherlands	1,559	nda	investment	480
Canada	1,460	1,200	turnover	479
Austria	965	nda	nda	
Australia	817	794	nda	
Greece	749	nda	nda	
Ireland	746	nda	construction	374
Sweden	571	nda	nda	
Norway	325	200+	turnover	50+
Korea	175	nda	nda	
Finland	86	3,000***	turnover***	320
Mexico	86	nda	turnover	1
Switzerland	12	350	turnover	100
*Wind turbine manufacturing industry, electricity production industries, institutes, and consultants.				
**Turnover in the wind turbine manufacturing industry including exports (4,402 million €) and turnover in the rest of the wind turbine sector.				
*** Jobs and turnover in the supply chain.				

## **5.2 Policy and support systems in Sweden**

In 2002, Sweden produced 70.3 TWh of electricity from renewable energy sources, of which about 90% were in the form of large scale hydro power. The EU and Sweden's Parliament have ambitious targets for the production of electricity from renewable energy sources and, in order to meet them, Sweden introduced its electricity certificate system in May 2003.

### **Electricity certificate system**

The objective of the electricity certificate system was originally to increase the production of electricity from renewable energy sources by 10 TWh by 2010, relative to the corresponding production in 2002. In 2006 the target level was raised and from 1st January 2007, the target is now to increase the production of electricity from renewable sources by 17 TWh in 2016, relative to corresponding production in 2002

Electricity producers whose electricity production fulfils the requirements in the Electricity Certificates Act receive one electricity certificate unit for each megawatt hour of electricity that they produce. Through the sales of their certificates, producers receive an additional revenue from and for their production of electricity. In this way, the system encourages the expansion of electricity production from renewable sources, and new technologies.

### **Suppliers**

Demand for certificates is created by the fact that all electricity suppliers – i.e. resellers, delivering electricity to end users – and also certain electricity users, are required to purchase certificates corresponding to a certain proportion (quota) of their electricity sales or electricity use.

In order to fulfil their obligations, the suppliers are required to submit an annual return to the Swedish Energy Agency with details of the amount of electricity that they have invoiced to their customers during the previous year, together with certificates corresponding to a certain proportion (quota) of their sales. These returns are required by not later than 1st March each year. In addition to electricity supply companies, the requirement to purchase a certain proportion of certificates (i.e. a quota obligation) also applies to electricity intensive companies and to electricity users who have used electricity that they have themselves produced, imported or purchased on the Nordic electricity exchange.

### **Quota obligation**

The quantity of certificates to be purchased increases from year to year in step with progressive increases of the quota proportion, thus generating a corresponding increase in demand for the certificates. In turn, this increases the incentive to produce more electricity from energy sources approved for production of electricity entitled to certificates.

The structure of the quota means that demand is relatively price inelastic, due to the fact that electricity suppliers have an incentive to purchase certificates up to a price that is 50% higher than the average price for the year. This is because, for each certificate that they do not cancel, they are required to pay a quota obligation charge

of 150% of the average price of certificates over a period of one year leading up to the date of cancellation.

The purpose of the electricity certificate system is to increase the production of electricity from renewable energy sources. Both competition and technical development have been important long term starting points for reducing the costs of electricity production from renewable energy sources, and thus for achieving the established target. If the target is to be achieved, the quota obligation must be increased as time passes. At the same time, such an increase must be based on a reasonable estimate of a likely increase in production of electricity from renewable energy sources.

The value of the quota is therefore set also with consideration of expectations of future electricity production from renewable sources and from peat, as well as with forecast values of electricity use in Sweden for each year.

### Restrictions on rights to certificates

The electricity certificate system is intended to support the construction of new plants for the production of electricity from renewable energy sources and from peat. However, in order to limit the cost to consumers of electricity from such sources as older, commercially viable plants, there is a time limit on the right of producers to receive certificates. Plants commissioned after the start of the electricity certificate system are entitled to receive electricity certificates for 15 years, or until the end of 2030, whichever is the earlier. Plants that were started up before the certificate system was introduced are entitled to certificates until the end of 2012. Plants that, at the time of their construction or conversion, received a public investment grant after 15th February 1998 (in accordance with a grants program for certain investments within the energy sector), are entitled to certificates until the end of 2014.

This will have the effect of reducing electricity production from renewable energy sources and from peat in the system, thus also reducing the number of certificates available. In order to adjust the demand for certificates, the quota will therefore be reduced in 2013, as can be seen in Figure 24.

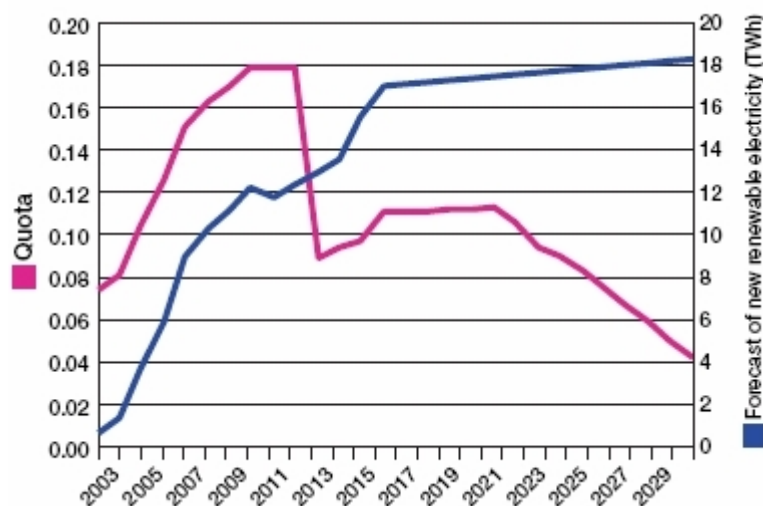


Figure 24: Quota obligations 2003-2030 and forecast of new renewable electricity production. [ref 27.]

A smaller number of plants will be phased out at the end of 2014, and so the increase in the quota will be correspondingly slightly flattened. However, the production plants that leave the certificate system in this way are expected to continue to produce electricity from renewable sources, as they will be commercially viable by then even without the additional revenue provided by the certificates. In total, renewable electricity production will increase, as certificates will have to be purchased from new plants.

### 5.3 Progress toward national objectives

In 2002, the parliament adopted a planning target for wind power output of 10 TWh/year before 2015. In principle, this means that wind energy should be considered in the spatial planning process such that it will be possible to actually build wind power to produce 10 TWh/year by 2015. The Swedish Energy Agency has distributed the national planning target of 10 TWh (4 TWh onshore and within territorial waters and 6 TWh offshore in the Swedish economic zone) by 2015 into regional targets and will follow up on them annually.

Regional volume targets take wind energy resources and regional electricity consumption into account. The purpose of the target is to elucidate wind power installations on regional and local planning levels. Moreover, the target will reduce planning and permission obstacles to create opportunities for 10 TWh of wind power by 2015.

For production, there is no goal for wind energy alone. The production goal in the electricity certificate system applies to new renewable energy in general. The electricity mix in Sweden is dominated by nuclear power and hydropower. Hydropower production varies from year to year due to the amount of yearly rainfall.

Figure 25 shows the installed wind capacity and production for 1998 through 2007.

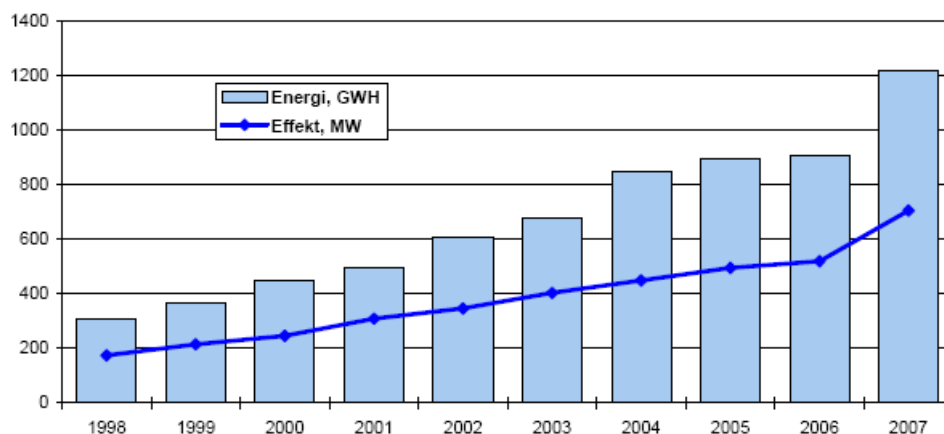


Figure 25: Installed wind energy capacity in Sweden 1998-2007 [ref 25]

For offshore wind power, the subsidy system is not sufficient for deployments to take off. There are no goals for offshore wind as such, but the government has had a special funding program for market introduction for large-scale plants offshore and in arctic areas with the intention to speed up the expansion of wind power in these large areas of Sweden.



The government has identified that progress toward a cost-efficient expansion of wind electricity is hindered by a slow permitting process for projects. The government therefore presented a Wind Power Bill in March 2006. The bill reduced the real estate tax for wind-power plants from 0.5% to 0.2% and made several suggestions that would facilitate the progress of wind energy expansion.

The suggestions included funding an additional 350-MSEK grant for the market introduction program, setting up a knowledge center for wind energy, providing financial support to municipalities for planning for wind power, defining new planning goals, and suggesting changes in the permitting process. The permitting process was changed in December 2006.

Prior to the change, all projects above 1 MW had to go through application procedures in connection with both the Environmental Act and the Planning and Building Act, with the permits decided by the county administration. The threshold now has been increased to 25 MW. For projects below 25 MW, all permitting matters are now handled by the municipality. Projects bigger than 25 MW are handled by the county administration (onshore permitting) or the Environmental Courts (offshore permitting).

### **Market characteristics**

Vattenfall and E.ON are the leading utilities for offshore wind energy development in Sweden. Smaller, yet also active, utilities include Falkenberg Energi, Göteborg Energi, and Skellefteå Kraft. The utilities develop projects on their own but also buy projects developed by independent developers at various stages of development. Several developers, among them WPD Scandinavia, Vindkompaniet, and RES Scandinavia, have as their strategy selling either portions of the project or the whole project to other investors. New investors are also entering the wind-power market in Sweden. One is Stena Renewable Energy AB, a subsidiary of the Stena shipping group. Other examples are the real estate company Lennart Wallenstam Byggnads AB and Vindin, formed and owned by a group of very large electricity-intensive industries in Sweden (forestry, steel, chemical, and mining industries). Vindin intends to build projects to produce 1 TWh/year, largely using land owned by companies in the group.

## **6 System aspects<sup>10</sup>**

A future energy system that includes a high proportion of renewable energy will be expected to meet the same requirements for security of supply and economic efficiency as the energy systems of today, while delivering better environmental performance, especially with regard to CO<sub>2</sub> emissions. Security of supply refers to the long-term reliability of fuel supply; especially in power systems, it also covers short-term requirements for system stability and adequacy. Economic efficiency is concerned with getting the best from the significant amounts of money, human capital and natural resources involved in an energy system. Integral to economic efficiency in energy systems is the presence of well-functioning markets for energy services. The variability and reduced predictability of a number of renewable energy sources, notably wind power, create specific challenges for future energy systems compared to those of today. Power transmission will also become an issue, as the

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10 Based on Sørensen, P., P. Meibom, O. Gehrke and J. Østergaard: Technical challenges to energy systems' operation and markets. In Risø Energy Report no. 5, Nov. 2006 edited by H. Larsen and L. Sønderberg. Risø-R-1557(EN)

areas with good potential for wind power are often located some distance from the centers of power consumption.

## **6.1 Managing power systems in normal operation**

Large wind farms such as the 160 MW Horns Rev and the 165 MW Nysted offshore wind farms in Denmark are connected to the transmission system, in a sense that make them comparable to conventional power plant blocks. To obtain the maximum benefit from an overall power system, wind power should be able to replace the operation of conventional thermal power plants, so that the fuel consumption and emissions can be reduced. To do this effectively, wind power plants need to possess some of the major characteristics of conventional power plants. One of these characteristics is the ability to control the amount and quality of the power produced. Modern wind turbine technologies make it possible to control both active and reactive power.

The possible power production from a wind power plant is obviously limited by the available power in the wind. Since the fuel is free the impact on operational cost for a wind farm is very limited when power output is reduced below the available power in the wind. Still, such reduced production can be beneficial in the overall system for periods where the market price of electricity is low or zero. In Denmark, this sometimes happens in cold and windy periods. Previously the electricity supply to the system was increased in cold periods because the Combined Heat- and Power Plants (CHP) plants have to run at high heat production and were obliged also to produce electricity for the grid. Recently, CHP plants are producing power also on market conditions and therefore the flexibility in the system is higher as the CHP plants are allowed to run in heat mode only.

### **6.1.1 Power control of wind power plants**

Horns Rev was the first large wind farm in Denmark. It is equipped with capable power control features, implemented through a wind farm main controller with remote access [ref 28]. Similar control features are provided at Nysted. The wind turbine technologies used at Horns Rev and Nysted are quite different, so the two wind farms may differ in their dynamic response to control requests. Their power control behaviour is quite similar, however, and has now become part of the Danish Technical Regulations for wind farms connected to the transmission system [ref 29]. Risø and Aalborg University have developed dynamic simulation models for wind farms. These models include wind farm controllers, individual wind turbine controllers, and the dynamics of the wind turbines themselves [ref 30].

Requests from the power system operator or the wind farm owner are specified as input to the wind farm controller. The wind farm controller measures the characteristics of the power generated by the wind farm at the point of common coupling to the grid (PCC). It then controls this power by issuing instructions to the individual wind turbines, each of which has its own controller. The wind farm controller also receives information from the turbines about the maximum amount of power available

A fundamental issue in the control and stability of electric power systems is to maintain the balance between generated and consumed power. This must be done with a relatively small time resolution, typically down to a few seconds.

Wind speeds can vary rapidly, so the output power from a wind turbine is characterised by short-term fluctuations. Large wind farms concentrated in relatively small geographical areas show a high degree of correlation between the power

fluctuations from individual generators, and this causes large fluctuations in the total power produced by the installation. Distributing wind power production over a wider geographical area has an overall smoothing effect, but the smoothing is less for large installations such as offshore wind farms concentrated in relatively small geographic areas.

An example of this is the experience of energinet.dk, the Danish transmission system operator, with the West Danish power system. Today more than 2,400 MW of installed wind power supplies approximately 20% of the electricity handled by the West Danish power system. Energinet.dk has found that the active power supplied by the first large offshore wind farm in this system, the 160 MW Horns Rev I, is characterised by more intense fluctuations in the minute range than previously observed from the dispersed wind turbines on land, even though Horns Rev I is small compared to the total wind power capacity in the system [ref 31]. A neighbouring wind farm, the 200 MW Horns Rev II, is scheduled to be commissioned in 2009, and energinet.dk is concerned about how this will influence the ability to regulate power in the system. Power fluctuations on a timescale of minutes are balanced by regulating power from generating plants that have a high degree of flexibility. The effect of power fluctuations from wind turbines on the need for regulating power should therefore be considered during long-term planning and cost optimisation, as well as in short-term planning such as the scheduling of maintenance.

### **6.1.2 State estimation**

With an increasing amount of power being generated by small, dispersed units connected to the distribution grid, the ability to obtain accurate information about the state of the power system becomes a key issue. Without better data, and the capacity to process it, the growing complexity of a distributed generation system becomes more and more of a burden, while its potential benefits, such as flexibility, remain difficult to harvest.

The life cycles of power transmission and distribution hardware—switches and circuit breakers, transformers, protection equipment, cables and lines—are measured in decades. While it is common for the latest generation of devices to provide remote monitoring and control services, the majority of units currently in service either completely lack these capabilities, or barriers such as vendor-specific communication and missing networkability reduce their usefulness. This is particularly severe at the lower voltage levels of the distribution system which are essentially invisible to system operators today.

Until a significant fraction of the older units have been replaced in the course of system development and maintenance—real-time information available through the system itself will be sparse. Distributed generating units could mitigate this problem, because their own controllers often measure system variables close to the grid connection point. Two new communication standards under development, IEC61400–25 for wind turbines and IEC62350 for distributed energy resources such as diesel generators, fuel cells and photovoltaic systems, are designed to provide access to these measurements in a standardised way.

New types of state estimators are required to integrate the different data sources into a coherent picture, to deal with continuity in a dynamic environment with many appearing and disappearing data sources, and to address issues related to the quality of data provided by power system end users, such as the owners of household CHP plants. To prevent bottlenecks and avoid creating new single points of failure in the face of a growing number of data sources, state estimation should be emancipated.

From being a capability of the system operator's control room, state estimation must be built into the system itself to provide a true ancillary service that is jointly provided at different locations in the grid, in a distributed fashion.

State estimation forms the foundation for different types of higher-level services, such as real-time assessment of security margins, fault detection, and on-line calculation of market-relevant data, such as identification of transmission congestions. Detailed, locally generated state information is also a precondition for advanced power system implementations, such as self-islanding/cells or meshed distribution networks.

### **6.1.3 Demand response**

The balance between generated and consumed power in a power system is maintained on an hourly timescale by the electricity spot market, and on a shorter timescale by various types of automatic or manual reserves provided by other markets. Consumption has a very low price-elasticity, and does in general not contribute to maintaining the balance of the system. Therefore, the generation system and cross-border exchange provide the needed flexibility and reserves.

Today's consumers are generally not provided with price signals from the markets, so they have limited chances to participate actively in keeping the balance. On the other hand, a wide range of loads—including electric heating, refrigeration, freezing and pumping—could potentially be moved from high-price to low-price periods at very low cost and without reducing service levels. Active participation of the demand side can thus provide a more efficient power system at lower cost.

Large scale development of wind power increases the need for active reserves in the system. First of all, reserves are needed to balance the wind power forecast errors on a timescale of hours, but also within the hour, on a timescale of minutes, wind power increases the need for reserves as discussed in the power fluctuation section above. These reserves are normally requested by the system operator, based on a market for regulating power. The demand side can also participate in such a market, provided that the necessary communication between the consumers and the market is available.

Another promising possibility is to use demand as a frequency-activated reserve operating on a timescale of seconds. Without any communication a simple electronic device can disconnect a load when the frequency is low and reconnect it when the frequency is again normal [ref 32]. This arrangement does not need a dedicated communication channel.

In the Nordic power system the frequency is outside the normal operating range for approximately 1% of the time; these excursions typically last for less than five minutes. Frequency-activated demand reserve would help to protect the system at times when it is most vulnerable, and would be especially helpful in recovering from faults such as the loss of a generator or a cross-border link. The benefits include:

- nearly instantaneous response would improve the frequency stability of the system
- the distributed grid connection points of the reserve improve stability
- low cost and best use of the available resources

A wide range of research is being carried out in Denmark to increase demand response. This includes a project to design a system for managing demand as a

frequency-activated reserve [ref 33]. This will answer questions including how to monitor and perhaps control the available reserve, whether some kind of communication is needed, for instance to set the trigger levels, the nature of the business models for transmission system operators, equipment suppliers and end users, and whether a market-based approach can be used.

#### **6.1.4 Challenges for market design**

Power is traditionally traded in a series of forward markets, so the amount of power to be produced and consumed within any given hour needs to be determined beforehand. In the case of Denmark, for instance, the Nordic power pool's day-ahead market (Nord Pool spot) operates 12–36 hours in advance.

A higher share of power that is only partly predictable, such as wind power, creates more deviations between the production planned in the forward markets and the actual power produced during the hour in question. Making up any shortfall requires calling on short-term regulating power, which is more expensive than power bought in the day-ahead market.

The extra costs of using regulating power are paid either by the producers or by the consumers, according to specific “imbalance settlement” rules set by the market. Whoever pays, it is important to ensure that the amount accurately reflects the cost of keeping the system in balance. A wind power producer, for instance, should not have to pay more than the actual costs incurred by wind power prediction errors [ref 34]. Risø is the coordinator of WILMAR, an EU-funded research project that is developing a planning tool for analysing the operational consequences of wind power prediction errors ([www.wilmar.risoe.dk](http://www.wilmar.risoe.dk)).

The shorter the timescale at which the power market can function, the more accurate the wind power forecasts will be. It will therefore become increasingly important to create intra-day markets that can trade closer to the actual delivery. A requirement for well-functioning intra-day markets should be for all power producers to make their regulation capabilities available for the intra-day as well as for the regulating power markets. The use of flexible power consumption (demand management) in the regulating power market can decrease regulation costs, so the development of market-based solutions to allow this should be continued [ref 34].

### **6.2 Managing power systems in fault mode**

The fault behaviour or “fault ride-through” capability of wind power plants is a key issue in the large-scale use of wind power in a power system. This is reflected in the grid codes—the rules that govern the behaviour of grid-connected wind turbines that are now in force in every country planning to develop wind power.

The purpose of fault ride-through is to ensure that wind turbines are able to stay connected to the grid during and after a grid fault. If the turbines are not able to stay connected through and after the fault, the consequence is a sudden loss of generation which must be replaced by fast reserves from other generators to prevent loss of load. Fault ride-through is not unique to wind turbines; similar capabilities are required of conventional generators to ensure that the system will continue to operate if one generating unit fails.

### **6.2.1 Power system stabilisation**

A fault or another disturbance on the grid causes the synchronous generators of large conventional power plants in one area to start oscillating against the synchronous generators in other areas. These oscillations affect the speeds of the synchronous generators, and hence the grid frequency. To dampen the oscillations, conventional power plants are often equipped with power system stabilisers. It may be a requirement for future large-scale renewable generation that it too is able to support power system stabilisation. Risø has developed stabilisation-promoting controllers for both fixed-speed active stall-controlled and variable-speed wind turbines. Descriptions of these controllers and simulation results are expected to be published in the near future.

### **6.2.2 Black start**

Another fault mode arises when part of the grid becomes isolated from the main synchronous system. If the isolated area is able to control its own frequency and voltage, a blackout can be avoided and the reliability of the power system improves. If the part of the system that is isolated is dominated by renewable and decentralised generation, then the contribution of these generators to the control of frequency and voltage can be the key to avoid substantial load shedding or even a blackout. If a blackout cannot be avoided, then it is important to re-start the system as fast as possible. This “black start” process can be supported by renewable and distributed generation, provided that these generators support frequency and voltage control. In cases like these, the dynamics of the power system control can be very important.

### **6.2.3 Reliability**

The reliability of wind power is an issue in normal operation as well as under fault conditions. From the point of view of the wind farm owner, reliability is considered mainly as the ability to sell power. In this case, a simple measure of reliability is the ratio of actual production to the energy available according to wind and power curves, taking into account failures in wind turbines and the grid itself. From the point of view of the system operator, reliability is mainly about the risk that all or some of the predicted wind power will not be produced.

A number of factors affect this measure of reliability:

- power forecasting errors caused by wind speed forecast errors -which generally cannot be avoided but probably reduced;
- if the wind speed rises to the “cut-out” speed of the turbines, production drops suddenly from rated power to zero;
- failures in the transmission line linking the wind farm to the transmission system;
- failures in the power collection grid within the wind farm;
- failures of wind turbines.

The three first mentioned are the most severe, because they typically involve the whole output from the wind farm. Failures of the internal grid or single wind turbines typically affect only a fraction of the production. A major research challenge is to build reliability models that combine general reliability factors, such as grid failures, with factors specific to wind power, such as wind forecast errors and cut-outs at high wind speeds.

## 6.3 Summary

The technical challenges to system operation and the power market are mainly about building a stable and reliable power system that contains a large scale of renewable energy to replace conventional power plants. In this context, a more specific challenge is to reduce the need to run conventional power plants at low output during periods when generation from wind power or other renewables is high. In such periods, conventional plants are kept running to provide ancillary services such as voltage and frequency support. The cost of the resulting power is high, in environmental as well as economic terms, because plants running below full capacity tend to be less efficient and more polluting. From an overall system point of view, therefore, it could sometimes be useful to use renewable generators to provide these ancillary services, even though this would reduce the total production from renewables.

# 7 Environmental issues

## 7.1 Land based projects

Wind energy is a clean and environmentally friendly energy source. There are no emissions to air or water, nor greenhouse gases, it requires no mining or drilling for fuel, and produces no toxic waste. However at the local and regional level wind energy can have impacts, in particular on humans, wildlife and/or habitats. Balancing these by-and-large local concerns against the unrivalled benefits to society is a difficult task, and one that requires both a general knowledge of many different issues and disciplines, as well as deeper understanding of complex issues combined with detailed and specific data on the environment.

Over the 30 years of implementation of modern wind turbines the three main environmental concerns have been visual impact, noise and the risk of bird-collisions. A best practice for how to undertake the environmental side of the wind farm planning and development have emerged as well. Key lessons are:

- Start early – environmental screening
- Avoid areas of special conservation importance with respect to any of the key concerns
- Involve relevant stakeholders
- Inform and involve neighbours

The site selection of a wind farm is the single most crucial action and should be accompanied with an appropriate screening of the environment involving the main issues.

Today noise is dealt with in the planning phase and normally it possesses few problems to build wind turbines close to human settlements. The visual effects of wind turbine may, however, create some controversy, as some people believe they are having a severe negative visual impact of the landscape, while others find them beautiful. Experience shows that it often pays to invest some effort in designing a good layout of the wind farm using well defined geometrical patterns while taking into the considerations the landscape features.

In some of the countries that installed wind turbines at an early stage, Denmark, Germany and Netherlands repowering has started i.e. small, old wind turbines are removed leaving space for modern and larger wind turbines. Denmark was the first country to actively support wind repowering, and the programs has led to the repowering of two-thirds of the oldest turbines in the country.

Denmark's first incentive program for repowering wind operated from April 2001 – December 2003. The second repowering scheme in Denmark was launched in 2005/06 but have been very slow partly due to a slowdown in planning efficiency (the responsibility of regional planning was shifted as a part of reform work on municipality and county level). At the same time groups of neighbours to projects with new large wind turbines have filed objections mainly due to visual impact from the new large turbines.

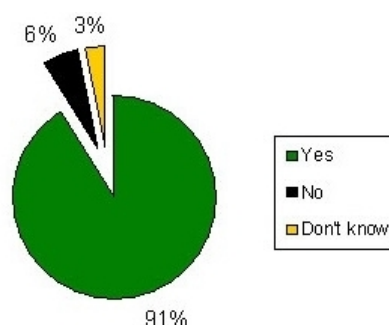
The environmental side of repowering is that the larger wind turbines have a slower rotational speed, which in general for most people has a less “aggressive” impact compared to the old fast-rotating turbines. On the other hand the modern turbines are taller and can be seen from a larger distance.

### 7.1.1 Public acceptance

From the public debate in Denmark on where to place new large wind turbines, the frontlines are often established in a very hard way to underline opinions. However, it seems that readers' contributions to the debate sections of the papers are often about uncertainty and imaginations of potential inconveniences. The overall impression of the public debate is that in general the population support wind energy but “not in my backyard”.

Meanwhile, all investigations show, that neighbours to wind turbines are the most positive when it comes to placing new wind turbines in their local area and it should be noted that opposing arguments are almost never about the existing more than 5,000 wind turbines in Denmark.

In an opinion poll conducted by ACNielsen for the Danish Wind Industry Association in February 2006 [ref 35] this is clearly documented. One of the main results is that 91% of the population is positive towards more wind energy in Denmark (Figure 26)



*Figure 26: Result of opinion poll in Denmark. The question is “Should Denmark continuously erect new wind turbines, so that an increasing share of the electricity production is covered by wind power? Source AC Nielsen 2006 [ref 35]*



A characteristic feature of the debate is that people living near wind turbines are significantly more positive; while the fraction that is negative is largest for people living with no wind turbines nearby. This may suggest that the protest that occasionally are filed by local residents are based on a lack of knowledge of facts and an uncertainty of what it will mean to me? Perhaps the need for new wind turbines is not sufficiently clearly communicated from the authorities (Government and municipalities)

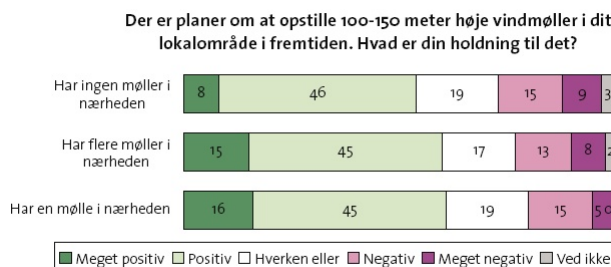


Figure 27: Result of opinion poll in Denmark. The question is “There are plans to erect large wind turbines in your local area (100-150 m high). What is your opinion on this? Green means positive; purple negative. Source Gallup 2007 [ref 35]

The impact on plants and animals is not very well established despite a sizable number of studies, but as it is with all power plants a certain amount of disturbance to flora, fauna birds and mammals will happen. With respect to wind energy the largest concern is on bird strikes and possible associated effects on resident bird population and migration paths. In general birds are able to navigate around the turbines in a wind farm and recent studies report very low bird mortality numbers in the order of 0.1 to 0.6 birds per turbine per year [ref.19]

In two countries (UK and US) radar and other electromagnetic signal interference from wind farms have been an issue of debate, while in many other countries this is not an issue [ref.20]. Also in Sweden radar and wind turbines have been investigated

during the period from 1995 to 2003 (ref 22) in a project called Sg Vind supported by Energimyndigheten (the Swedish Energy Authority). The results of the Sg Vind project were that it established a basis for the Swedish defense forces (Försvarmakten) to evaluate and approve wind farms on land. Following the project a larger number of wind farms on land have now been accepted by the Swedish Defense Forces.

At the same time the Sg Vind project the demonstrated that concerning offshore wind farms the existing basis for approval was not sufficient and a new project concerning impact on radar systems from offshore wind energy was needed. This project was called Flygprov radar and was implemented during 2007. The view of the Swedish Defense Forces is that in periods where the coastline of Sweden and the prevailing direction is perpendicular to each other radar reflections from the offshore wind farms will create a “shadow” behind the wind farm where the radar signals does not reveal any information. Field tests with boats and aircraft was planned as a part of the project.

All experience dealing with the environmental impacts of wind projects show that dealing with the issues early and openly and enter into dialogue with relevant stakeholders will normally facilitate working out a solution satisfying all parties. Software tools for analysis and presentation to the public of the environmental impact of wind farms are available, which includes noise calculation, visualization and photomontage for illustration of visual impact as well as calculation of shadow flickering.

## **7.2 Environmental factors for offshore projects**

The shallow waters around the North European coasts of the North Sea, the Baltic Sea and the English Channel offers good conditions for offshore wind farms. These areas combine shallow water with a good wind resource. At the same time these areas host millions of breeding, migrating and wintering water birds, with large congregations occurring in specific areas. With present plans to develop more large offshore wind farms in especially Denmark, UK, Sweden, Germany and Holland, it is increasingly important to study how this development can be taken forward with minimum impact upon the environment.

### **The Danish experience**

Like wind farms and other infrastructure projects on land it is obvious that offshore wind farm projects will have an impact on their natural surroundings. However, the Danish experience from the past 16 years shows that offshore wind farms, if placed right, can be engineered and operated without significant damage to the marine environment. Since 1991 a total of 8 offshore or near-shore wind farms have been commissioned with a total installed capacity of 423 MW from 213 wind turbines in the range from 450 kW to 2.3 MW – and one 3 MW.

#### **7.2.1 The Danish Offshore Monitoring Programme 1999-2006**

Before, during and after the construction of the two large wind farms Horns rev (160 MW) and Nysted (165 MW) an environmental monitoring programme was launched to investigate and document the impact of these two wind farms. The results were published on 27-28 November 2006 at an international conference in Ellsinore [ref.16].

The studies and analyses have dealt with:

- Benthic fauna and flora, with particular focus on the consequences of the introduction of a hard-bottom habitat, which is the turbine foundation and scour protection, this also included a survey of the in-fauna community in the wind farms.
- The distribution of fish around the wind turbines and the scour protection, and the effect of electromagnetic fields on fish.
- Studies of the numbers and distribution of feeding and resting birds, performed by aerial surveys, and of the food choice of scoters.
- Migrating birds, including study of the risks of collision between birds and wind turbines.
- The behaviour of marine mammals – porpoises and seals – and their reaction to wind farms.
- Sociological and environmental-economic studies.
- Coastal morphology.

Below the findings on benthic communities, fish, marine mammals, birds and people are summarised.

### Benthic communities and fish

For both wind farms new artificial habitats developed quickly. At Horns Rev, the new habitats have increased diversity and biomass in the area, whilst in the Nysted offshore wind farm, monocultures of common mussels have developed due to the low salt content in the area and the absence of such predators as starfish. The artificial habitats are expected to have positive effects on fish populations, both with regard to the number of species and the quantity of fish, once the artificial reef is fully developed.

### Marine mammals

During construction every effort was made to frighten seals and harbour porpoises away from the area before the extremely noisy work of inserting piles and sheet pile walls began, so as to avoid harm being done to them. After completion the seals have returned to both areas and have generally seemed unaffected by offshore wind farm operations both at sea and on land.

During the construction phase, the number of porpoises at the farms decreased immediately when noisy activities commenced, alleviating fears that marine mammals would remain in the area and so might be hurt by the intense pressure waves generated by pile driving. At Horns Rev the porpoise numbers very quickly returned to “normal” once construction was completed, although data on porpoises at Nysted are different and more difficult to interpret.

### Birds

Potential hazards to birds include barriers to movement, habitat loss and collision risks. Radar, infrared video monitoring and visual observations confirmed that most of the more numerous species showed avoidance responses to both wind farms, although responses were highly species specific. Birds tended to avoid the vicinity of the turbines and there was considerable movement along the periphery of both wind farms.

The study confirmed that the sea birds and divers are good at avoiding the offshore wind farms either by flying around them or by flying low between the wind turbines, and therefore the risk of collisions is small. Of a total of 235,000 common eiders passing Nysted each autumn, predicted modelled collision rates were 0.02% (45 birds). The low figure was confirmed by the fact that no collisions were observed by infra-red monitoring.

Concerning loss of habitat post-construction studies initially showed almost complete absence of divers and scoters within the Horns Rev wind farm and significant reductions in long-tailed duck densities within the Nysted wind farm. Other species showed no significant change or occurred in too few numbers to permit statistical analysis.

The fact that no common scoters were observed inside the wind farm area lead to the perception that they had been forced out of their previous feeding grounds, even though this had only insignificant effects on the level of population. Then in late 2006 and early 2007 Vattenfall A/S maintenance crews and helicopter pilots reported increasing numbers of common scoters present within the wind farm site. On that background a series of four surveys of water bird distribution in the area was programmed during January to April 2007 (ref.17).

The results from these four aerial surveys carried out in 2007 show that, in contrast to the earlier years post construction, common scoter were present in significant

numbers between the turbines at Horns Rev 1. It can therefore be concluded that Common Scoter may indeed occur in high densities between newly constructed wind turbines at sea, but this may only occur a number of years after initial construction.

#### Public acceptance

Public attitudes to offshore wind farms have also been examined. This part of the study consisted of a sociological survey with in-depth interviews with local residents both in the Horns Rev and Nysted areas and an environmental economy survey, in which local questionnaire surveys were supplemented by surveys among a national reference group.

The Horns Rev offshore wind farm is located 14 km west of Blåvandshuk in an area dominated by holiday homes with only 3,300 permanent residents. The offshore wind farm is only visible from just a few houses. The Nysted offshore wind farm is located 10 km from the coast and some of the approximate 4,300 permanent residents in the area can see the wind farm from their homes. The wind farm is also visible from Nysted harbour.

The environmental economy survey shows that more than 80% of the respondents are either positively or extremely positively disposed towards offshore wind farms. The greatest support is to be found in the area around Horns Rev, whilst there were most negative reactions in the Nysted area, though opposition here was restricted to a mere 10% of the respondents. The latter may relate to the fact that the township of Nysted is located close to the shore and thereby to a higher degree exposed to aviation warning lights placed on the nacelles of the turbines on the outer edges of the wind farm.

A clear willingness to pay (via electricity bills) to reduce visual impact was found. In the Horns Rev sample, respondents were willing to pay 261 DKK/household/year to have the distance from the shore extended from 8 to 12 km and 643 DKK/household/year to have the distance extended from 12 to 18 km. There was no extra willingness to pay to have wind farms moved from 18 to 50 km from the shore. In the Nysted area, respondents were willing to pay nearly twice as much as in the Horns Rev sample.

Furthermore the sociological survey showed that the original opposition in the Blåvandshuk area has gradually diminished after the Horns Rev offshore wind farm was commissioned, and by 2004 the general attitude was neutral or even slightly positive.

#### **7.2.2 Important results of the Danish environmental programme.**

The comprehensive environmental monitoring programmes of Horns Rev and Nysted wind farms confirm that, under the right conditions, even big wind farms pose low risks to birds, mammals and fish, even though there will be changes in the living conditions of some species by an increase in habitat heterogeneity.

The technological tools developed in the Nysted and Horns Rev studies, especially for the study of behavioral responses of marine mammals and birds, will be very useful for researchers working on new offshore wind farms in other locations. Among others these involve the so-called T-POD system, which measures the supersonic activities of harbour porpoises within the offshore wind farms and in the test areas, and TADS technology, which measures bird collisions. These technologies can readily be transferred to estuarine or open sea sites and applied for study of a wide range of focal species.

The results of the environmental monitoring programme in general show that it is possible to adapt offshore wind farms in a way which is environmentally sustainable and which causes no significant damage to the marine environment. Territorial planning, which identifies the most suitable locations, is crucial in this context. In the light of the programme, offshore wind farms now in many ways stand out as attractive options for the development of sustainable energy, as long as authorities and developers respect the marine environment.

### **Natura 2000**

Natura 2000 is an ecological network in the territory of the European Union designed to protect the most seriously threatened habitats and species across Europe. Natura 2000 is founded on two EU directives, the Habitats Directive and the Birds Directive adopted in 1979. Each EU Member State must compile a list of the best wildlife areas containing the habitats and species listed in the Habitats Directive and the Birds Directive. These lists are then be submitted to the European Commission, after which an evaluation and selection process on European level will take place in order to appoint the Natura 2000 sites. Natura 2000 protects 18% of land in the 15 countries that formed the EU before the expansion in 2004.

### **Sweden, UK and Holland**

The Swedish Environmental Protection Agency (Naturvårdsverket) and the Swedish Energy Authority (Energimyndigheten) launched an environmental monitoring program (kunskapsprogrammet Vindval) in 2004 with a total budget of 35 mio. SEK. The program includes a total of nearly 20 research projects on the environmental impact from wind on fish, mammals and birds as well as a sociological survey. The program was due to end at the end of 2007 and several reports are available now (June 2008). Two new issues were studied in Sweden as a part of Vindval project:

One project was studying the visibility of offshore wind power plants to birds while taking the visual physiology of birds into account. The project used telespectrophotometry to estimate the perceived contrast between offshore wind turbines and their background during various weather conditions. Two locations were studied: Utgrunden I offshore wind farm as well as two lighthouses in Kalmarsund and two lighthouses in Öresund.

The knowledge that comes from such a study may facilitate the development of bird-adapted paint schemes for wind turbines that do not increase their visibility to human observers. The results (ref 23) show that the wind turbines at Utgrunden I, as well as the simulated wind turbines in Kalmarsund and by Lillgrund in Öresund are more visible to birds than to humans, especially at close range. It appears that the paint scheme applied at Utgrunden I offshore wind farm is fairly well adapted both to reduce the risk of bird collisions and at the same time to limit the aesthetical impact to human observers.

The second new issue in Vindval was to study behaviour of bats offshore and near wind farms. The aim was to find out whether bats are exposed to any collision risk offshore. Previous studies of bats were done but only for land based wind farms. Observations were made at Utgrunden and Yttre Stengrund in Kalmarsund in the Baltic Sea and in Öresund between Sweden and Denmark from onboard boats and at the coastal points where bats take off. Ultrasound detectors, strong portable spotlights and thermal cameras were applied in the studies. The results (ref 24) showed bats offshore in numbers exceeding the expectations before the study. The

studies revealed that the bats were hunting insects near the sea surface but also near the wind turbines of Utgrunden and Yttre Stengrund wind farms in Kalmarsund. Most observations were done in fine weather with low wind speeds ( $< 2.5$  m/s) when insects gather around the turbines. Furthermore most bats fly at low altitudes, typically below 10 m but bats were observed as high as 40 m.

Prior to this study it was completely unknown that many bat species, both migratory and non-migratory, regularly use this food resource on the open sea far from the coasts in the late summer and early autumn.

For the wind farm Utgrunden and Yttre Stengrund both located in Kalmar sound extensive monitoring of bird migration were carried out in 1999 to 2003. This is a very busy area for migration of sea birds. Each year approximately 1.3 million birds are passing by. A calculation of collision risk based on the observations shows that 1-4 birds in spring and about 10 birds in autumn run the risk of colliding with the existing 12 wind turbines. The waterfowl that make an evasive manoeuvre due to the wind turbines extend their total migrating distance and time by only 0,2 – 0,5 %.

For the wind farm North Hoyle (60 MW) in the UK commissioned in November 2003 Jamie May PMSS Ltd, at the Copenhagen Offshore conference October 2005 ended his presentation on the environmental impact assessment with the conclusion that for a wind farm placed away from sensitive species and habitats basically no negative impact were found.

A UK research program COWRIE (Collaborative offshore wind research into the environment) was established in 2001 by The Crown Estate. The aim of the program is "to conduct generic environmental research into the potential impacts of offshore wind farm development". The first round of COWRIE allocated over £450,000 to six research projects. Fifteen additional projects were launched in 2003 when The Crown Estate ran a competitive tender for a second round of offshore wind farm development.

The research areas have so far been:

- Birds and benthos
- Electromagnetic fields
- Marine bird survey methodology
- Remote techniques
- Underwater noise and vibration

In the Netherlands a large monitoring program has been launched to monitor effects from the first Dutch offshore wind farm Egmond an Zee (108 MW) completed in April 2007. The first results are due to be published later in 2008.

## **8 Research and development**

### **8.1 Introduction**

During the last 30 years of modern wind energy deployment, national and international R&D programs have played an important role in promoting development of wind turbines towards more cost effectiveness and reliability. The

interaction between industry and national R&D programs has been important for the development of effective turbines all the way from the early beginning in the 1970s.

## **8.2 Important research areas**

As earlier described the three bladed up wind machines seems to have won the race regarding the wind technology. The concept was based on the historical experiences with utilizing the wind power many places in the world and experiments from the mid 70<sup>th</sup> after the energy supply crises in the world. Experiments with different concepts have not led to constructions that have been able to beat the horizontal 3 bladed up-wind turbine. In the beginning most of these turbines were stall regulated, but to day most of the MW turbines are pitch regulated.

During the past a large number of R&D projects have been carried out and influenced the development. Some of the most important results have been related to understanding the aerodynamics and the design of the rotor blades and the turbines. Together with developments of new material for blades this has enable the possibilities to make the large MW turbines, which to day are dominating the market.

Another R&D area have been research in wind resources, which to day have resulted in wind maps in many countries and models for calculating and forecasting the day to day wind resources at sites where wind farms are planned to be built. As more wind power is being built also integrating the wind power into the grid systems together with the other electricity production units has become a major research area. One of the reasons is of course that that most wind turbines are directly connected to the grid and use the grid to balance the power and as a kind of storage.

## **8.3 Future Technology R&D**

Continued R&D is essential to provide the necessary reductions in cost and uncertainty to realize the anticipated level of deployment. Continued R&D should also support revolutionary new designs as well as incremental improvements. The challenge is to try to find those evolutionary steps that can be taken to further improve wind turbine technology.

Basic R&D continues to be of high importance and will contribute to further cost reductions and improved effectiveness in all technology development lines. The re-emergence of large turbines of 2 MW and over requires a greater understanding of machine loads and the response of the structure. For instance there are large uncertainties in the incident wind field, which has increased spatial variation for larger swept areas. Currently the largest turbines are used both onshore and offshore, but these technologies may diverge in future. Basic R&D on loads and structure will contribute equally to both these development tracks.

Offshore wind energy is currently an important element of development and R&D for Denmark, Germany, the Netherlands, Sweden, the UK and the United States. Whilst offshore wind energy substantially exploits existing knowledge and research work from onshore wind, a number of important new areas require R&D to improve the level of understanding and optimise solutions. There are also a variety of different environments for offshore wind in terms of sea state, sea bed, depth and floating structures. The challenges specific to offshore wind energy include the understanding of loads from the combined forces of wind, waves and ice, support structures for shallow and deep waters ( $\geq 30$  m), floating support structures and methods for the transportation, installation and maintenance of turbines. Machine

sizes will also continue to grow until the package of turbine and installation is optimised.

Future R&D must also include incremental improvements in, for example, understanding extreme wind situations and reducing system weight.

Future research projects can therefore be expected within areas such as:

- g) Reduction of uncertainties  
Forecasting power performance, reducing engineering uncertainties especially in large machines and improving standards.
- h) Cost reduction  
Improved site assessment, better models for aerodynamics/aeroelasticity, new concepts, more efficient components, stand alone systems.
- i) Enable large-scale use  
Electric load flow control and adaptive loads, improvement of power quality.  
Integration of large (500 MW +) wind farms
- j) Minimise environmental impacts  
Compatible use of land, quieter turbines, effects on flora and fauna onshore and offshore, recycling.
- k) Wind within future energy supply systems.  
Wind energy in combination with long and short term energy storage.  
Wind energy in combination with hydrogen generation.  
Wind energy in combination with other renewables.

An important element in connection with turbine R&D is access to good test facilities. Generally there is a need for more test facilities for both onshore and offshore wind turbines to be able to test large blades, drive trains and new materials to verify models and to test turbines in harsh environment like offshore and cold climate.

## **8.4 System issues**

There are three main categories of wind system integration considered here; grid-connected electricity generation, Off-grid (including mini-grid) electricity generation and energy supply applications. As well as the direct generation of electricity feeding both large transmission systems and mini-grids, wind can be exploited as an energy source to power other plant. In particular it can be used to generate hydrogen as an energy transfer medium.

### **8.4.1 Grid-connected system integration**

Because of the expected growth in the contribution from wind, the system integration of wind energy into national and international electricity supply systems is an immediate priority area. It has high relevance to all the member countries over the short to longer term. For several member countries grid integration issues will present the primary challenge to the expansion of wind power in the medium term.

Because of the different characteristics of wind generation and its connection into networks, operators are concerned about effects on system stability, the operation of existing plant and costs. Offshore wind farm economics favour very large installations, typically entering the high voltage transmission system. Wind energy power plant of this nature is new to the transmission system operators, who are



concerned to evaluate the effects on their overall operations. The development of validated models that enable network operators to reliably predict and regulate system behaviour will greatly reduce resistance to the continued expansion of both onshore and offshore wind energy. This will have a strong influence on policy decisions over the next ten years and will be a key factor in accelerating deployment. Within the IEA Wind Implementing Agreement the following topics have been identified as the most important in addressing the future grid-integration of wind energy.

- l) Large scale grid integration; modelling and management of load flows within national and international high voltage transmission networks.
- m) Distributed generation; modelling the system response to wind energy embedded in the low voltage distribution networks.
- n) The development of detailed models, describing turbine and large wind farm electrical behaviour.
- o) Better forecasting techniques increasing the value of wind energy by allowing electricity production to be forecasted from 6 to 48 hours in advance.
- p) Improved electrical storage techniques for different time scales (minutes to months) will increase value at penetration levels above 15 to 20%.
- q) Regeneration and active demand side management.
- r) Energy storage.
- s) The value and benefits of combining wind energy with other technologies such as hydro and PV.
- t) The organisational and legal framework for transmission and distribution system operators to provide a safe and reliable electricity supply.

In addition to challenges associated with the integration of the technology to produce electricity, wind energy could be used to produce other energy carriers such as hydrogen. Wind energy technology has traditionally been used in producing electricity and will be continuing to do so in the future. But, innovative concepts in hybrid systems and storage techniques may benefit other sectors of the economy and the fight against climate change.

#### **8.4.2 Off-grid generation**

Stand alone or off-grid systems have the capability to bring a reliable and cost effective electricity supply to many remote locations. Whilst the total installed capacity will remain low in comparison to grid-connected wind, the value of such systems can be very high. Off-grid electricity supply systems usually combine wind with complimentary technologies such as diesel and PV. They benefit from energy storage, often using batteries and require a control system.

The small size of this market to date has discouraged technology investment and research is needed to improve both the turbine technology and the rest of the system. Experience to date has been of reliability and availability well below the larger turbines. This, compounded by difficulties in servicing and spares supply, has led many small systems to fall into disuse. The size of the market is sensitive to perceptions about reliability and cost and improved technology will expand the market which includes remote areas and islands within countries with large rural areas like many developing countries.

#### **8.4.3 Other wind energy applications**

R&D to facilitate integration of wind generation into the electrical grid and R&D on demand side management will be essential when large quantities of electricity from wind will need to be transported through a grid.

A number future application can help integrate larger amount of wind power like;

- a) plug-in vehicles (benefits: energy storage and transportation) - need for demonstration
- b) production of clean
  - a) production of hydrogen
  - b) wind power plant in combination with hydro power station incl. pumped storage - need for demonstration
- c) combine wind and wave plant suitable for shallow water

## **8.5 International projects**

### **The UPWind Project**

UpWind is a European project funded under the EU's Sixth Framework Programme (FP6). The project looks towards the wind power of tomorrow, more precisely towards the design of very large wind turbines (8-10MW), both onshore and offshore.

The challenges inherent to the creation of wind farms of several hundreds MW request the highest possible standards in design, complete understanding of external design conditions, the design of materials with extreme strength to mass ratios and advanced control and measuring systems geared towards the highest degree of reliability, and critically, reduced overall turbine mass.

The wind turbines of the future necessitate the re-evaluation of the turbine itself for its re-conception to cope with future challenges. The aim of the project is to develop the accurate, verified tools and component concepts the industry needs to design and manufacture this new type of turbine.

UpWind focuses on design tools for the complete range of turbine components. It addresses the aerodynamic, aero-elastic, structural and material design of rotors. Critical analysis of drive train components will be carried out in the search for breakthrough solutions.

The UpWind consortium, composed of 40 partners, brings together the most advanced European specialists of the wind industry. The findings of the project will be disseminated through a series of workshops.

## **8.6 R&D areas in Sweden**

Sweden is today characterized by not having any major wind turbine industry. Therefore most of the projects<sup>11</sup> over the last years have been related to the siting of wind farm and the integration of wind power into the grid system. Elforsk, the Swedish Electricity Utilities' R&D company, manages the program. Basic research projects are funded 100% by the Swedish Energy Agency and applied projects are funded 60% by Elforsk and 40% by the Swedish Energy Agency. The program is user-oriented and has strong co-operation between the utilities and the grid owners (including the Swedish TSO). Areas of research interests include grid integration,

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<sup>11</sup> "2006 IEA Wind Energy Annual Report and the Elforsk Program: Vindforsk 2003-2006 and 2006-2008

external conditions, standards, O&M, project development, impacts on the environment, and public acceptance.

Apart from projects in these programs R&D projects regarding mapping the wind climate in Sweden and conflicts with the military radar reconnaissance also have been funded. To improve market competition and to help the development of new turbines that can lower the cost of electricity, the Swedish Energy Agency has funding a special demonstration project of a 3.5-MW turbine with a new direct-driven generator, NewGen. The recipient of the financial support for the demonstration project is Vattenfall AB. The turbine is expected to be in operation by mid-2009. The generator will cut weight by approximately 70% compared with a conventional direct-driven generator, which is believed to cut generator cost by about half and make the drivetrain investment cost comparable to that for a conventional gearbox/high-speed generator concept. The benefit of the direct driven generator will be a reduced number of components, better reliability, and reduced O&M costs.

As mentioned above it is continued R&D is considered to be essential to provide the necessary reductions in cost and for future installation not least for offshore applications. It can therefore be recommended, that Sweden continue to fund R&D projects within the different wind energy areas.

## **8.7 Novel Technologies**

### **8.7.1 New wind turbine technologies**

While a significant consolidation of the wind turbine design took place in the 80'ies and 90'ies a large development effort continue today. The main drivers for the current technology development are:

- cost of power
- reliability
- grid compatibility
- visual appearance
- acoustic performance

In the USA the Department of Energy (DoE) has laid out a five-year plan for wind energy R&D that follows three paths:

- Land-based electricity path: Here the focus is on low wind speed technology and machines in the range 2–6 MW. The main barriers are transmission capacity, and the goal for 2012 is \$0.03/kWh at 13 mph (5.8 m/s) sites.
- Offshore electricity path: The focus is on both shallow and deep water with turbine sizes of 6 MW and larger. The main barriers are cost and regulation, and the goal for 2012 is \$0.05 /kWh.
- Emerging deployment paths: Here the focus is not on wind alone, but also on hydrogen and clean water. The barriers are cost and infrastructure, and the 2020 goals are custom turbines for electricity, hydrogen production and desalination.

### **8.7.2 Superconducting generators for wind turbines**

At Risø DTU a project is launched towards development of a 10 MW generator based on so-called high-temperature superconductor (HTS) materials (operating at

77K – the boiling point of Nitrogen). Traditionally superconducting materials used in e.g. hospitals Magnetic Resonance Imaging scanners are based on low temperature superconductors requiring liquid helium. The new wind turbine generator can be kept at 77K by an advanced cryogenic refrigeration plant and is expected to contribute the following advantages:

- A 50 – 60 % reduction in weight and size compared to today's generator
- A multi-pole design makes direct drive possible and avoids the use of gear-boxes
- Removing the gear-box is expected to give less maintenance of the generator
- Reduced operation and maintenance costs

### **8.7.3 New offshore concepts**

Although the offshore market is only 1.3% of the world market (installed MW in 2006) many new technology developments are first seen offshore. There are many reasons for this. The development offshore started much later than on-shore development and is not as mature. At the same time offshore is the most challenging environment for application of wind power with a harsh environment and difficult access, which calls for autonomous designs with very high reliability. Furthermore the relatively high cost for foundations and grid connection drives the size of the wind turbines towards larger units in order to reduce generation costs. In some countries e.g. USA and Norway locations outside the visibility zone are considered in order to eliminate possible conflicts with people living near the coast. The water depth outside the visibility zone (> 25 km) in these waters is significant and leads to new challenges.

As offshore oil and gas runs low the production facilities are likely to be transformed from pure fossil fuel based towards hybrid/renewable energy facilities adding wind, wave and solar devices for generation of electricity and later also fuels for the transport sector. A first sign of this development is seen in the North Sea at the Beatrice oil field off the coast of Scotland. The prototype installation consist of two 5 MW wind turbines at water depths of 42 m and the power from the wind turbines can cover approximately one third of the needs of the nearby oil production platform (Figure 28).



*Figure 28: The Beatrice wind farm consisting of two 5 MW wind turbines in 42 m deep water. The wind farm is connected to an existing oil production facility. Source [www.beatricewind.co.uk](http://www.beatricewind.co.uk)*

In the US in 2004, the Offshore Wind Energy Consortium financed by the US Department of Energy, General Electric and the Massachusetts Technology Collaborative announced a project to consider technology for water depths from 50 ft to 100ft (20-35 m). Same year a company called Atlantis Power LLC launched a financing scheme for \$2 million for 3 x 2MW wind turbines to be operated in 120 m water depth. In March 2006, GE announced a \$27 million partnership with the U.S. Department of Energy to develop 5 to 7 MW turbines by 2009, supplanting the company's current 3.6-megawatt turbines.

Japan has also been investigating offshore wind development [ref.14]. Japan has a national target of 3000 MW by 2010 (current status is 1500 MW total on and offshore) which will be the equivalent of 0.5% of national electricity consumption. There are several areas within wind speeds above 8 or 9 m/s at 60 m height but the contour of 20 m water depth is only about 2 km from the coastline. Ryukyu University has developed the 'hexa-float' system made of concrete with 10 m sides and a 10 kW prototype is planned. Also under consideration is a stable floating platform for two turbines in a diamond shape which has been tested in a water tank as has the spar type floating structure.

In Norway two competing projects, Hywind (Norwegian Hydro, Statoil) and Sway (Statoil, Statkraft, Lyse Energi, Shell) both are developing floating offshore wind farm concepts for deep water (200-300m). Both are based on wind turbines rated at 3-5 MW or larger and the sub-sea structure is made of concrete. The main difference between the two concepts is the mooring principle. Recently Hywind has received 59 mill NOK financial support from the Norwegian Government for their prototype off

the cost of Norway to be installed in 2009 while the companies behind Sway have managed to raise the necessary funds for the prototype from private investors.

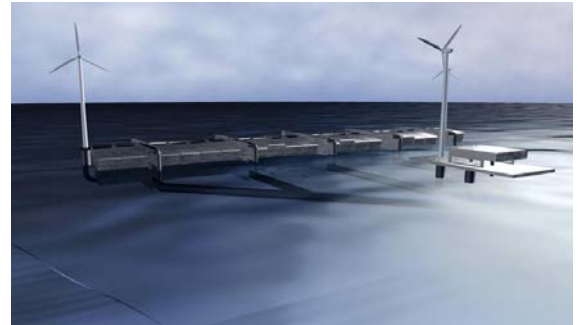
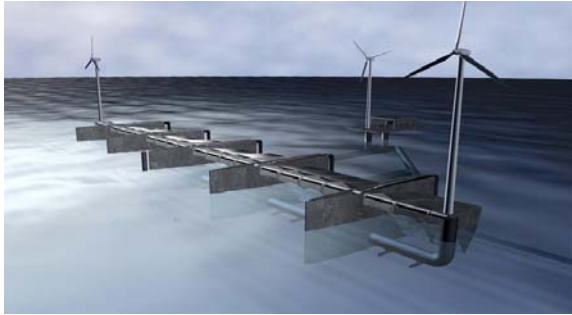


*Figure 29: The floating wind turbine concept Hywind. Source: Norwegian Hydro and Solberg production.*

### **Offshore wind and wave**

Poseidon's Organ is a hybrid power plant transforming waves and wind into electricity – a floating offshore wave power plant which also serve as foundation for wind turbines. The concept has been tested in wave tanks in scales up to 1:25. Late in 2007 a 1:6 scale model rated at 80 kW wave power and measuring 25 by 37 m will be launched off the coast of Lolland, Denmark in connection with the first offshore wind farm in Denmark at Vindeby. The full size plant (Figure.30) is designed to be 230 m by 150 m and is expected to be placed off the coast of Portugal, and will be characterized by:

- 35 percent of the energy in the waves is transformed to electricity
- 30 MW generation capacity including three 2 MW wind turbines
- 28GWh annual generation if located in the Atlantic off the Portuguese west coast
- 22GWh annual generation from the three wind turbines



*Figure.30: Computer image of Poseidon's Organ. The front of the full size wave power plant is 230 metres wide and consists of 10 floats. The floats absorb the energy inherent in the waves. A double functioning pump transforms the wave energy into a water flow driving a turbine producing electricity. Source [www.poseidonorgan.com](http://www.poseidonorgan.com)*

#### **8.7.4 Grid connected small wind turbines**

In the decentralised energy societies of the future the large (but distant) centralised energy facilities will be supplemented by an extensive integration of renewable energy in everyday life (micro-generation). Examples of this is facades and other building elements integrated with solar photovoltaic elements and small wind turbines designed and optimised for use at the point of energy demand. Two examples of this trend is the small 6 kW wind turbine from Quietrevolution Ltd. and a combined solar PV and a small wind turbine integrated with a outdoor lightning system (Figure 31 and Figure 32) The idea is that the pole and the grid connection for the lamp are needed anyway. Both are then designed to serve the wind turbine as well as a solar PV installation.



*Figure 31: Quietrevolution wind turbine for integration in cities and on buildings.*

Ref. [www.quietrevolution.co.uk](http://www.quietrevolution.co.uk)



*Figure 32: The Hybrid Tower Wind & Solar Power Outdoor lighting System from Matsushita, Japan. Ref [www.panasonic.co.jp](http://www.panasonic.co.jp)*

### 8.7.5 Vertical axis concepts

This section outlines some of the advantages and disadvantages of vertical axis wind turbines compared to the traditional horizontal axis wind turbines.

Vertical-axis wind turbines (VAWT) are commonly referred to as drag driven or lift driven devices. The energy is taken from the wind by a component of the lift force working in the direction of rotation. The same principle is used for a horizontal axis wind turbine (HAWT), except that the axis of rotation is practically horizontal.

The Savonius wind turbine is referred to the above first category of VAWTs, whereas the Darrieus wind turbine is to the latter. An example is shown in Figure 33.



*Figure 33: Drag-driven vertical wind turbine (Savonius type)*

The Darrieus rotor is a vertical-axis wind turbine (VAWT) provided with two or more blades having an aerodynamic airfoil. The blades are normally bent into a chain line and are connected to the hub at the upper and lower side. A Darrieus rotor with straight blades (fixed pitch) have been developed, with large hubs provided and spokes (H-Darrieus or Giromill). Further developments have been made to articulate the blade pitch in a cyclic manner during one revolution (Cyclo-turbine).

A series of demonstration projects has been carried out since the late 70-ties with small size VAWTs with rated power up to 100-300 kW and various rotor shapes. The largest demonstration project was carried out with the EOLE 3.6 MW Darrieus wind turbine. Figure 34 shows a variety of different configurations. The presently largest VAWT demonstration wind turbine is shown in Figure 35. In Figure 36 a variety of different historical H-rotors is shown, for which the UK LTD turbine is a visualisation based on a conceptual study.

Finally Figure 37 shows a few commercial available H-rotors on the market that are equipped with permanent/magnetic generator type and inverter. This development has been pushed forward with the Heidelberg 300 kW VAWT with MAGLEV type generator. Hybrids between the concepts have been worked on in studies, for example the Wagner rotor and the different designs from Ole Ljungström.

It should be noted that in spite of large R&D investments especially in the 1980'ies the VAWT concept was not brought to a commercial stage.





Figure 34: From left to right: Guy-wired (300 kW FloWind, 500 kW Sandia, 250 kW Chinook) and self-supporting (15 kW Tumac, 100 kW Fokker, Vestas tandem) Darrieus VAWTs

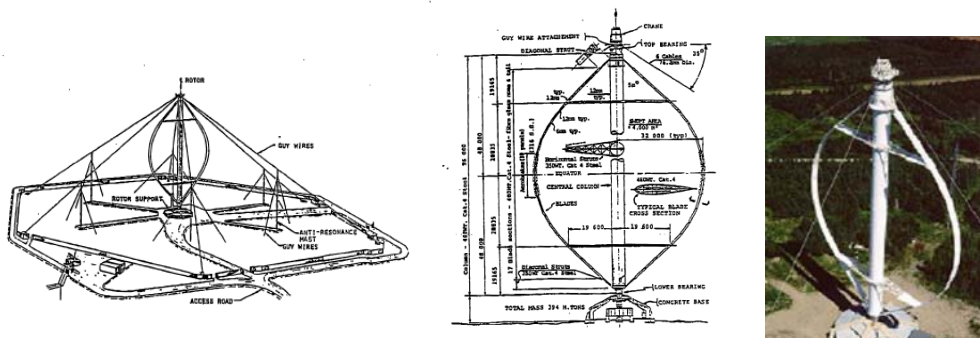


Figure 35: Project EOLE design configuration, and photo of 3.6MW prototype.



Figure 36: H-Rotors. Left-to-right: 300 kW Heidelberg rotor (MAGLEV generator), 500 kW VAWT, 3 MW UK LTD (concept study)



Figure 37: Commercially available Giromills. Left-to right: 55 kW, 1.2 kW, 0.3 kW, Marc Power Systems and QR5, UK and 3 kW Turby

### **Specific differences between the VAWT and HAWT.**

Aerodynamically- VAWTs with high tip speed ratio are operating aero- dynamically at unsteady conditions, where cyclic loads appear on the blades and in equilibrium with constant gravitational load. For HAWTs cyclic varying gravitational loads are introduced for the revolving blades during a revolution. This reflects the aerodynamical performance and structural loading when the wind turbines are subject to wind shear.

- Present literature [ref 36] point to the fact that VAWTs are less sensitive to wind shear variability than HAWTs because the blades are turning in horizontal, vertical and intermediate positions.
- VAWT blades can be extruded from aluminum. A similar process intended for HAWT blades is not possible. HAWT blades can be structurally and load wise optimized.
- Aerodynamical efficiency for Darrieus rotors (aerodynamically not optimized profiles) are 10% less than for HAWT rotors (aerodynamically highly optimised profiles).
- On the electrical side new generator concepts like multi-pole permanent generator/inverter and variable speed have been introduced for VAWTs, whereas HAWT generator principles incorporate initially traditional, either fixed speed or variable speed and 'normal' generator types (non permanent synchronous –asynchronous). Recently however permanent magnet generators are introduced for the HAWT.
- The Darrieus concepts operation are based on a stall-regulated control (fixed pitch), whereas H-rotors as mentioned can utilise variable pitch. HAWTs are similarly operating with both concepts (stall-and pitch control, and hybrids).
- The starting torque coefficient for a Darrieus rotor is zero and at low tip speed ratios it is even negative. Therefore a special motor is required to start the rotor. This is not necessarily a disadvantage in terms of safety aspects.
- H-rotor gains on power performance because of straight blades, but has high centrifugal loads and parasitic drag effects on struts.
- Fatigue issues can probably be avoided under certain circumstances for Darrieus rotors, though demonstration projects in the past indicated major fatigue problems (extruded blades). HAWTs are improving within fatigue issues and fatigue records, though it is not to avoid completely.

Additionally a comparison of the advantages and disadvantages of VAWTs and HAWTs are summarized in Table 17 [ref 37].

Table 17: Advantages and disadvantages of VAWTs and HAWTs

HAWTs	
Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Are exposed to the slightly higher wind speeds that occur at these elevations.</li> <li>• Require less ground area since they usually use free standing towers.</li> <li>• Have constant aerodynamic loading with constant angle of attack.</li> </ul>	<ul style="list-style-type: none"> <li>• Require drive train be placed atop a tower.</li> <li>• Require heavier towers - drive train located at tower top.</li> <li>• Require expensive and troublesome yaw drive systems.</li> <li>• Maintenance carried out high above ground often using expensive cranes.</li> <li>• Cantilevers used extensively: <ul style="list-style-type: none"> <li>– high bending moments on blades;</li> <li>– high overturning moments on foundation.</li> </ul> </li> <li>• Blade tips and drive train noise may propagate due to high tower heights.</li> </ul>
VAWTs	
Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Omnidirectional - no yaw equipment.</li> <li>• Have drive train at ground level: <ul style="list-style-type: none"> <li>– easier to operate and maintain.</li> </ul> </li> <li>• Simpler design - no yaw gear, drop cables, etc.</li> <li>• Lower cost installation: <ul style="list-style-type: none"> <li>– due to reduced over turning moments and lower tower top mass.</li> </ul> </li> <li>• Have non-cantilevered blade supports.</li> <li>• May be quieter due to lack of blade tips and ground mounted drive train.</li> <li>• Unexplored technology may offer more potential for cost reductions.</li> </ul>	<ul style="list-style-type: none"> <li>• Have a low rotor height which reduces rotor wind speed.</li> <li>• Have lower tip-speed ratio for peak aerodynamic efficiency. Higher torque means more expensive gearboxes.</li> <li>• Require more area due to the guy wires.</li> <li>• Aerodynamic torque ripple provides cyclic loading on drive train.</li> <li>• Longer blade length, about twice the length of HAWTs. Blades are major wind turbine cost item - low cost blades are essential to VAWTs.</li> </ul>

In the authors opinion two issues should be included in Table 17 above under VAWT disadvantages:

- Fatigue problems for blades
- Power and speed control in strong winds no as obvious as for HAWT

A comparison of the two concepts at equal power output shown in [ref 37] indicates that the foundation loads in a critical wind regime with wind speeds of 60 m/s are almost one third of the foundation loads for a HAWT. It is apparent that the tower and foundation for a VAWT can be constructed significantly lighter than the HAWT equivalent in this extreme situation.

Because of the commercial success of HAWTs and technical problems and limitations concerned with VAWTs originating back to the 80ties only a minor focus has emerged on small VAWTs for urban use- like the Marc Power System, Ropatec, QR5 or Turby BV wind turbine. However, the cost for a 3 kW Turby is approximately 12,000 Euro and approximately 50,000 Euro for the 10 kW QR5.

Today HAWTs have been constructed in multi-MW sizes and put in operation on land as well as offshore, with a fast increasing marked for offshore operated HAWTs. Presently the offshore HAWTs are mounted on steel piles or concrete pillars in shallow waters, while in some countries an increasing interest for floating offshore wind turbine units is emerging (See paragraph 8.7.3 above).

As indicated previously some theoretical studies are today carried out for large scale, offshore VAWT application with particular interest of the H-rotor type, with a typical representation covered by [38]. Positive features for offshore VAWTs are

highlighted, mainly related to a stipulated lower maintenance cost compared to HAWTs maintenance costs as derived from present wind farm projects.

It should be emphasized that comparison of a concept mostly known from theoretical studies and prototypes (VAWT) with a commercially well developed concept (HAWT) includes a significant uncertainty.

## 9 Scenarios for deployment of wind power

### 9.1 Estimates of onshore wind power prospects in 2015, 2030 and 2050

A rapid development in the global utilization of wind power has taken place over the last 10 years. At the end 2007, about 1% of the global electricity consumption was produced by wind power.

As shown in Table 18 the growth in total capacity have been between 20 and 30 percent yearly over the last five years and in many countries significant amounts of capacity is in the planning stages. In the near future BTM Consult estimates a doubling of the annual wind power development alone in the period from 2006-2011.

*Table 18: Growth in wind energy capacity from 2001 - 2006*


Year:	Installed MW	Increase %	Cumulative MW	Increase %
2001	6,824		24,927	
2002	7,227	6%	32,037	29%
2003	8,344	15%	40,301	26%
2004	8,154	-2%	47,912	19%
2005*	11,542	42%	59,399	24%
2006	15,016	30%	74,306	25%
<b>Average growth - 5 years</b>		<b>17.1%</b>		<b>24.4%</b>

*Source: BTM Consult ApS - March 2007*

Several estimates of the future development have been made. The BTMs [ref.1] forecast (Table 19 and Figure 38) is based on very detailed market information collected over a longer period of years.

BTM Consult estimates a doubling of the annual wind power development alone in the period from 2006-2011. This would bring the total capacity above 200 GW.

*Table 19: Forecast 2007-2011.*

	Cumulative installed capacity (MW) by end of in 2006	Installed capacity (MW) in 2006	Forecast 2007-2011 (incl. Offshore)					Installed capacity between 2007-2011	Cumulative installed capacity (MW) by end of 2011
	2006	2006	2007	2008	2009	2010	2011	Sum	Accu.
Total Americas	13,577	3,515	4,850	5,700	6,250	7,750	8,500	33,050	46,627
Total Europe	48,627	7,682	8,610	9,760	12,030	13,150	15,600	59,150	107,777
Total South & East Asia	8,963	3,220	4,340	5,110	5,650	5,800	6,950	27,850	36,813
Total OECD-Pacific	2,617	485	725	1,000	1,150	1,250	1,400	5,525	8,142
Total other areas	522	114	275	410	650	885	1,050	3,270	3,792
Total MW new capacity every year:		15,016	18,800	21,980	25,730	28,835	33,500	128,845	203,151
Accu. capacity (MW)	74,306		93,106	115,086	140,816	169,651	203,151		

Source: BTM Consult ApS - March 2007

The forecast has been split into forecast 2007-2011 and predictions 2012-2016. The forecast is based on market information from national energy plans in a number of countries, and world market indicators. The prediction is an overall analysis based on the forecast and published potentials in major areas of the world. According to this forecast, the global capacity increases by a factor of 6 from today's approximately 75,000 MW to 450,000 MW in year 2016. This is equivalent to about 5% of today's electricity consumption.

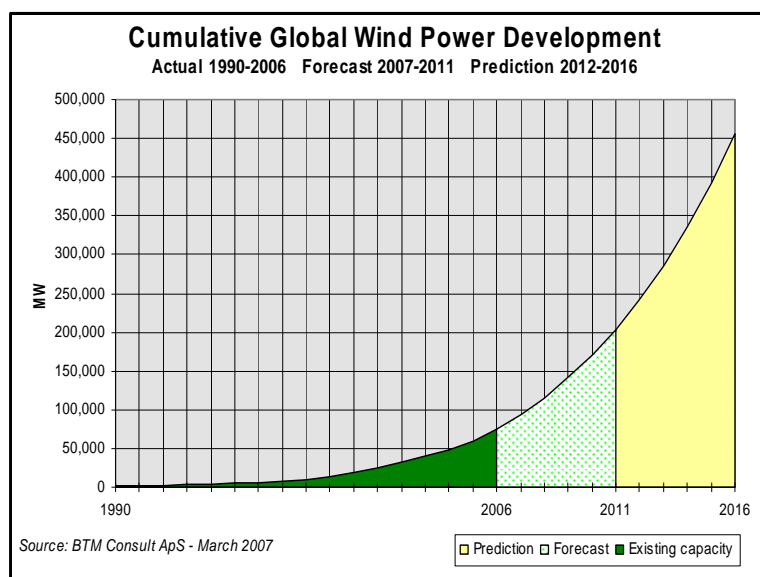


Figure 38: BTM's global wind energy forecast March 2007 [ref 1].

Several international institutions and agents such as IEA, the European Wind Energy Association, Greenpeace [ref 3] and GWEC have also formulated scenarios ending with as much as 12% of the electricity consumption 2030 to be covered by wind power.

## 9.2 Scenarios for the future development of wind power

In the last two decades wind power has developed rapidly. For 15 years annual growth rates in total accumulated capacity has ranged within 20 to 35%. At present the wind power market is characterized by a strong demand implying supply constraints within the turbine manufacturing industry and no signs indicate that demand will diminish within the coming years (BTM market world market updates [ref.1]). Turbine manufacturers and sub suppliers are expanding their manufacturing capacity and new companies are entering the arena. In the light of a growing concern for climate change and security of energy supply - increasing prices for fossil fuels, high crude oil prices - expectations are that the wind power industry also in coming years will witness a rapid growth.

Based on existing studies on future wind power development [ref. 3] and [ref. 5] Risø DTU has evaluated future opportunities in wind power and calculated a future scenario for wind power deployment. It should be strictly underlined that results shown in this chapter are subject to large uncertainties.

The following assumptions are used in the Risø wind power scenario:

- The present rapid growth within the overall wind power industry of approx. 25% increase in total accumulated capacity will continue until 2015, including both on- and offshore capacity. Up and downs will exist, but on average the growth rate will be 23% annually. The high demand will be driven by increasing demand for energy in developing regions (as China), increasing environmental concerns and by increasing fossil fuel prices.
- As the wind industry grows more mature capacity growth rates for on- and offshore wind power will decline, to 17% on average in the period 2015-20, to approx. 10% in 2020-30 and, to 2.4% in 2030-50.
- The capacity factor will on average be 25% for on land turbines (2200 full load hours) for the whole period until 2050, covering that new wind turbines will have a higher production being moderated by a lower availability of sites with high wind speeds. Correspondingly, the capacity factor for offshore installations will on average be 37,5% (3300 full load hours) until 2050
- The global expected final electricity consumption will follow existing forecasts [ref. 15] and [ref. 3]; that is approx. 2.8% annual growth until 2030, followed by an assumed slower growth of 1.5% p.a. in the period 2030-50.

Based on the above-mentioned assumptions, the future scenario for wind power development is given in Table 20.

*Table 20: Scenario for global on and offshore wind power development.*

	Total installed Wind GW	Yearly growth rate of wind %	Production from wind total TWh	Expected electricity consumption TWh	Penetration of wind %
2006	74		163	15500	1.1
2015	486	23	1084	21300	5.1
2020	1066	17	2392	23800	10.1
2030	2633	9.5	6019	29750	20.4
2050	4200	2.4	10100	40100	25.2

As shown in Table 20 total wind power production (on land and offshore) is calculated to be 10,100 TWh in 2050, wind power supplying approx. 25% of global electricity consumption. The assumed growth implies that the accumulated global wind power capacity will double each 3<sup>rd</sup> year until 2015, each 4<sup>th</sup> year from 2015-20, and, each 7<sup>th</sup> year from 2020-30. In the period 2030-50 growth will be much slower.

On land wind power will constitute the vast bulk of this development, offshore mainly starting in the period up to 2020, becoming increasingly important until 2050.

Table 21 shows the development of on land turbines until 2050.

*Table 21: Scenario for global on land wind power development.*

	On landwind GW	Yearly growth on land wind %	On land of total wind power, %	Production from on land wind, TWh	Expected electricity consumption TWh	Penetration of on land wind, %
2006	73		98.8	160	15500	1.0
2015	474	23	97.4	1042	21300	4.9
2020	1024	17	96.0	2252	23800	10.7
2030	2382	9	90.5	5240	29750	17.6
2050	3430	1.8	81.6	7542	40100	18.8

As shown in Table 21 the total on land wind power production is calculated to approx. 7,500 TWh in 2050, supplying approx. 17.6% of global electricity consumption and constituting approx. 81.6% of total wind power capacity. The assumed growth implies that the accumulated global on land wind power capacity will double each 3<sup>rd</sup> year until 2015, each 5<sup>th</sup> year from 2015-20, each 7<sup>th</sup> year from 2020-30. In the period 2030-50 growth rates will be much lower.

### **9.3 Long-term cost perspectives for on land turbines**

Until 2004 the cost of wind turbines in general followed the development of a medium-term cost reduction curve (learning curve) showing a learning rate of approximately 10% that is each time wind power capacity was doubled the cost was reduced by approx. 10% per MW-installed. This decreasing cost-trend was interrupted in 2004-6 where the price of wind power in general increased by approx. 20%, mainly caused by increasing material costs and a strong demand for wind capacity implying scarcity of wind power manufacturing capacity.

Although at present a large number of wind-projects are carried out worldwide each year, do to confidentiality reasons it gets increasingly difficult to get trustworthy investment and O&M-costs. Based on the available data it is calculated, that today's expected investment costs for a new on land wind turbine will on average be 1.2 mill.€MW, with a minimum of of 1.0 mill.€MW and a maximum of 1.4 mill.€MW

In the following the long term cost development of on land wind power will be estimated using the learning curve methodology. However, learning curves are not

developed to be applied for that long a time period and for this reason the estimated figures are mainly to be seen as the results of a long term scenario development.

The long term cost perspectives for on land wind power is shown in Table 22 given the following conditions:

- The total capacity development of wind power (Section 9.2) is assumed to be the main driving factor for the cost development of on land turbines, because the major part of turbine costs are related to the general wind power industry development.
- The existing manufacturing capacity constraints for the wind turbines will persist until 2010. Although we gradually will see an expanding industrial capacity for wind power, a continued increasing demand will also continue to strain the manufacturing capacity and not before 2011 increasing competition among wind turbine manufacturers and sub suppliers will again imply unit reduction costs in the industry.
- For the period 1985 to 2004 a learning rate of approx. 10% was estimated [ref.6]. With the return of competition in the wind industry again in 2011 this learning rate is again expected to be realized by the industry in the period until 2020. The wind power industry growing mature the learning rate is assumed to fall to 6% in 2020, in 2030 decreasing further to 3% keeping this level until 2050.

Given these assumptions minimum, average and maximum cost-scenarios are reported in Table 22 below:

*Table 22: Scenarios for cost development of on land wind turbines, constant 2006-€.*

	Investment costs, Mill. €MW			O&M	Cap. factor
	Min	Average	Max	€/MWh	%
2006	1.0	1.2	1.4	12	25
2015	0.86	1.03	1.20	10	25
2020	0.76	0.92	1.07	9	25
2030	0.70	0.84	0.99	8	25
2050	0.69	0.83	0.97	8	25

As shown in Table 22 the average cost of offshore wind capacity is calculated to decrease from 1.2 mill.€MW in 2006 to 0.83 mill.€MW in 2050 or by approx. 30%. A considerable spread of costs will still exist, from 0.69 mill. €MW to 0.97 mill.€MW. A capacity factor of constant 25% (corresponding to a number of full load hours of approx. 2200) is assumed for the whole period, covering an increasing production from newer and larger turbines moderated by sites with lower wind regimes

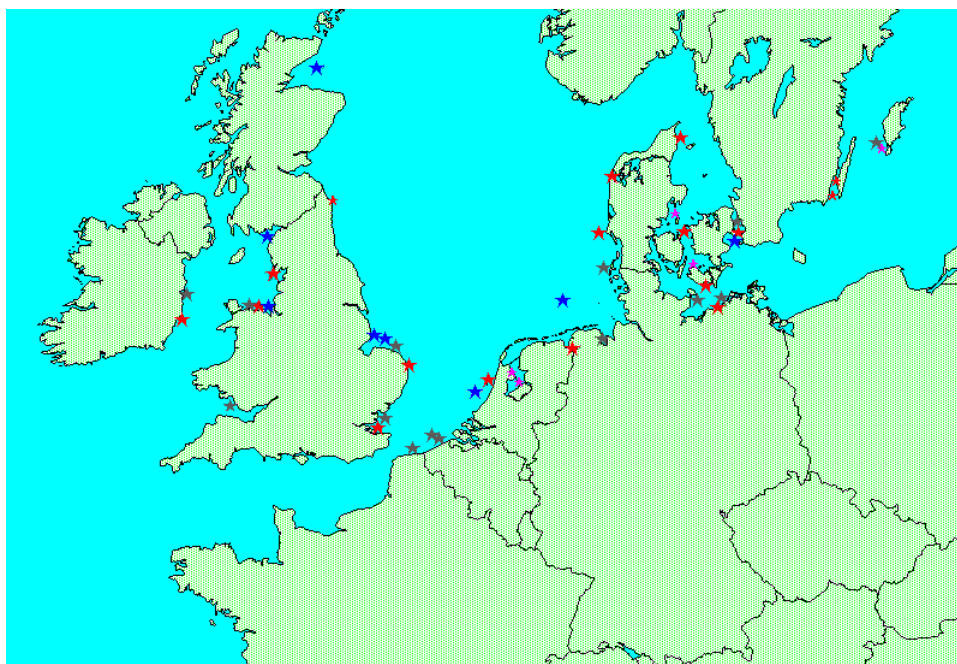
## 9.4 Offshore wind power prospects in 2015, 2030 and 2050

### Offshore wind farms under construction and in planning stage

At present several offshore wind farms are under construction in UK waters (Robin Rigg, Rhyl Flats, Inner Dowsing and Lynn) and in Dutch waters the second offshore farm Q7- renamed to Prinses Amalia wind farm (4. June 2008) consisting of 60 2 MW turbines will be operational in 2008. And much more offshore capacity is in the



planning stages. In the United Kingdom, for example, London Array Limited received consent in December 2006 for the world's largest offshore wind farm to be built in the London Array. At 1,000 MW of capacity, it will be capable of powering one-quarter of the homes in London. In Denmark another 2 times 200 MW will be installed in 2009 and 2010.



© 2002 [www.offshorewindenergy.org](http://www.offshorewindenergy.org). "Stars": red = (built MW wind turbines), purple = (built small wind turbines), blue = (under construction), grey = (planned)

Figure 39: Map of existing and planned offshore wind farms in North-West Europe

#### 9.4.1 Future Danish offshore projects

The Committee for Future Offshore Wind Turbine Locations published the report: "Future Offshore Wind Turbine Locations – 2025" in April 2007. The report charts a number of possible offshore areas where offshore turbines could be built to an overall capacity of some 4,600 MW. Offshore wind turbines with a capacity of 4600 MW could generate approximately 18 TWh, or just over 8% of total energy consumption in Denmark. This corresponds to approximately 50% of Danish electricity consumption. The committee has examined in detail 23 specific possible locations each of 44 square kilometres to an overall area of 1012 square kilometres divided between 7 offshore areas (Figure 40).

The committee has assessed society's interests in relation to grid transmission conditions, navigation, the marine environment, the landscape, raw material exploitation etc. The committee has also assessed options for connecting major offshore wind farms to the national grid, including examining the engineering, economic and planning options for landing power and the consequences for the underlying grid of the various potential areas for construction. At the same time the committee described scenarios for technological development of wind turbines capable of installation at greater sea depths. The committee attached importance to a planned and coordinated expansion of wind power and the transmission network with a view to obtaining the greatest possible economic benefits.

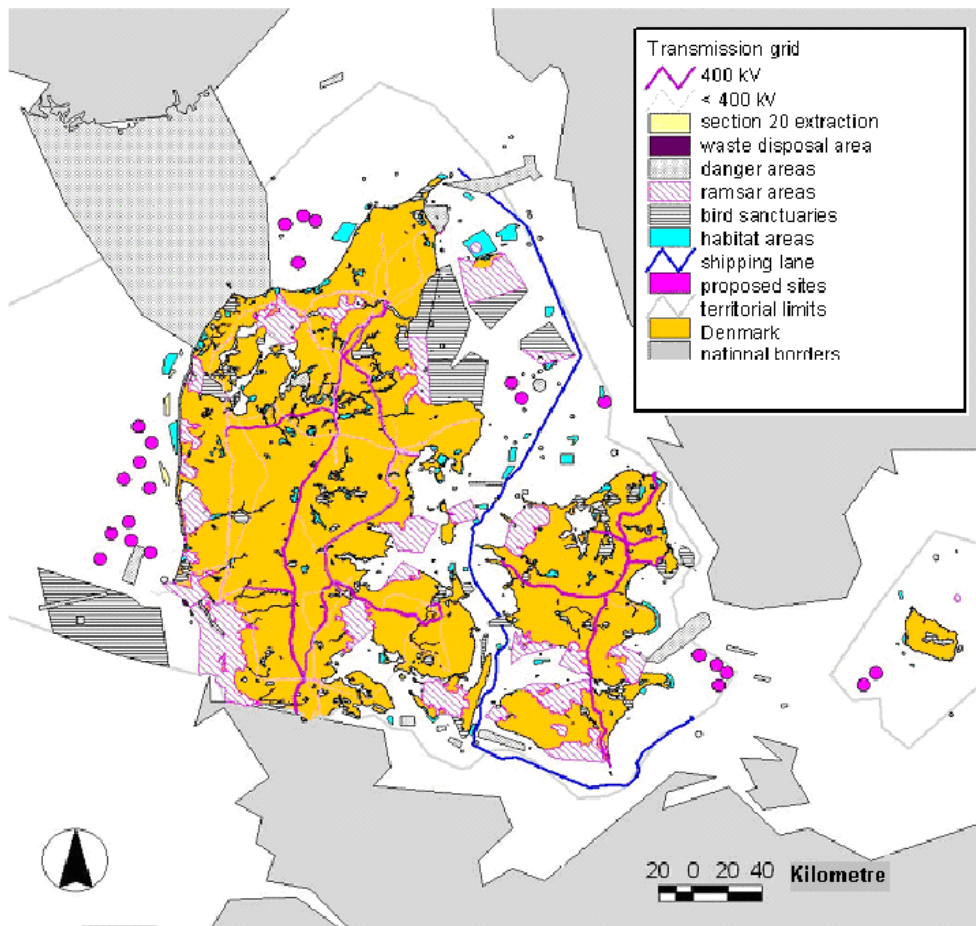


Figure 40: Potential locations for future offshore wind farms around Denmark

### Scenarios for the future offshore development of wind power

In the last two decades wind power has developed rapidly. For 15 years annual growth rates in total accumulated capacity has ranged within 20 to 35%. At present the wind power market is characterized by a strong demand implying supply constraints within the turbine manufacturing industry and no signs indicate that demand will diminish within the coming years [ref.1]. Turbine manufacturers and sub suppliers are expanding their manufacturing capacity and new companies are entering the arena. In the light of a growing concern for climate change and security of energy supply - increasing prices for fossil fuels, high crude oil prices - expectations are that the wind power industry also in coming years will witness a rapid growth.

To some degree offshore development will follow the picture outline for the total wind power development outlined in chapter 3.6, but a few exceptions do exist. The following specific assumptions are made for offshore wind power development:

- Mainly based on existing plans offshore wind power development is assumed to grow by approx. 34% p.a. until 2015. Growth rates are expected to fall after 2015 to approx. 27% in the period 2015-20, to 20% in 2020-30 and, to a little more than 5% in 2030-50.
- The capacity factor will on average be 37,5% for offshore turbines (3300 full load hours) for the whole period until 2050, covering that new wind turbines will have a higher production being moderated by a lower availability of sites with high wind speeds.

Based on the assumptions, the future scenario for offshore wind power development is given in Table 23.

*Table 23: Scenario for global offshore wind power development.*

	Offshore wind GW	Yearly growth offshore wind %	Offshore of total wind power, %	Production from offshore wind, TWh	Expected electricity consumption TWh	Penetration of offshore wind, %
2006	0.9		1.2	3	15500	0.0
2015	12.8	34	2.6	42	21300	0.2
2020	42.4	27	4.0	140	23800	0.6
2030	251.1	19.5	9.5	829	29750	2.8
2050	773.8	5.5	18.4	2559	40100	6.4

As shown in Table 23 total offshore wind power production is calculated to 2,559 TWh in 2050, offshore wind power supplying a little more than 6% of global final electricity consumption and constituting approx. 18.4% of total wind power capacity. The assumed growth implies that the accumulated global offshore wind power capacity will double each 2<sup>nd</sup> to 3<sup>rd</sup> year until 2015, each 3<sup>th</sup> year from 2015-20, and, finally, each 5<sup>th</sup> year from 2020-30.

## 9.5 Long-term cost perspectives for offshore turbines

Until 2004 the cost of wind turbines in general followed the development of a medium-term cost reduction curve (learning curve) showing a learning rate of approximately 10% that is each time wind power capacity was doubled the cost was reduced by approx. 10% per MW-installed. This decreasing cost-trend was interrupted in 2004-6 where the price of wind power in general increased by approx. 20%, mainly caused by increasing material costs and a strong demand for wind capacity implying scarcity of wind power manufacturing capacity.

A similar increase in price is witnessed for offshore wind power, although a fairly small number of realized projects in combination with a large spread in investment costs make it difficult exactly to identify the price level for offshore turbines. On average expected investment costs for a new offshore wind farm will today be in the range of 1.9 to 2.2 mill.€/MW.

In the following the long term cost development of offshore wind power will be estimated using the learning curve methodology. However, learning curves are not developed to be applied for that long a time period and for this reason the estimated figures are mainly to be seen as the results of a long term scenario development.

The long term cost perspectives for offshore wind power is shown in Table 24 given the following conditions:

- The total capacity development of wind power (Section 9.2, Table 20) is assumed to be the main driving factor also for the cost development of

offshore turbines, because the major part of turbine costs are related to the general wind power industry development. However, a faster development of offshore capacity is expected and also a number of cost issues (foundation, transmission cables etc.) are specific for offshore, which by now are expected to have considerable cost reduction potentials. For that reason the total wind power capacity development is used in combination with higher learning rates for offshore development than seen for onshore.

- The existing manufacturing capacity constraints for the wind turbines will persist until 2010. Although we gradually will see an expanding industrial capacity for wind power, a continued increasing demand will also continue to strain the manufacturing capacity and not before 2011 increasing competition among wind turbine manufacturers and sub suppliers will again imply unit reduction costs in the industry.
- For the period 1985 to 2004 a learning rate of approx. 10% was estimated (ref. 9). With the return of competition in the wind industry again in 2011 this learning rate is again expected to be realized by the industry. Because offshore wind power is a relatively young and immature area, this learning rate is assumed to persist until 2030, where after the learning rate is assumed to fall to 5% until 2050.

Given these assumptions minimum, average and maximum cost-scenarios are reported in Table 24.

*Table 24: Scenarios for cost development of offshore wind turbines, constant 2006-€.*

	Investment costs, Mill. €MW			O&M	Cap. factor
	Min	Average	Max	€/MWh	%
2006	1.8	2.1	2.4	16	37.5
2015	1.55	1.81	2.06	13	37.5
2020	1.37	1.60	1.83	12	37.5
2030	1.20	1.40	1.60	12	37.5
2050	1.16	1.35	1.54	12	37.5

As shown in Table 24 the average cost of offshore wind capacity is calculated to decrease from 2.1 mill.€MW in 2006 to 1.35 mill.€MW in 2050 or by approx. 35%. A considerable spread of costs will still exist, from 1.16 mill. €MW to 1.54 mill.€MW. A capacity factor of constant 37.5% (corresponding to a number of full load hours of approx. 3300) is assumed for the whole period, covering an increasing production from newer and larger turbines moderated by sites with lower wind regimes and increasing distance to shore and thus increasing losses in transmission of power.

## 9.6 Scenarios for Sweden seen in a global perspective

A number of scenarios for the future development of wind power in Sweden are calculated. These scenarios point to a strong Swedish development. In [ref 39] wind power in Sweden is forecasted to grow from 1 TWh in 2005 to approximately 11 to 21 TWh in 2020, implying a growth rate of 17% p.a. and 23% p.a., respectively.

In comparison the global scenarios adopted for on land and off shore turbines show the following growth rates:

- For on land turbines a growth rate of 23% p.a. is assumed until 2015, then declining to 17% until 2020. On average a growth rate of 19% p.a. from 2006 to 2020.
- For off shore turbines a growth rate of 34% p.a. is assumed until 2015, then declining to 27% until 2020. On average a growth rate of 29% p.a. from 2006 to 2020.

How the development of Swedish wind power will be distributed on land and offshore turbines are not known to us. Nevertheless, seen in the light of the global scenarios the Swedish growth rates between 17% p.a. and 23%p.a. seem not to be out of reach, although it will require strong planning and policy initiatives to maintain growth rates as the mentioned ones.

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